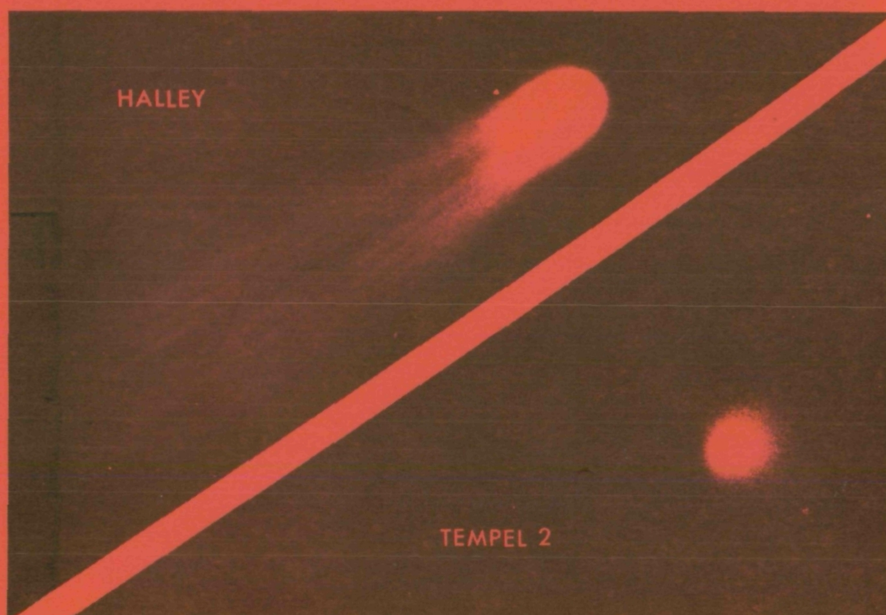
NASA Technical Memorandum 80543

REPORT OF THE COMET SCIENCE WORKING GROUP



August 1979

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Space Administration
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CONTENTS

PART ONE

GENERAL RECOMMENDATIONS

SECTION I

SUMMARY AND CONCLUSIONS

This report summarizes the principal conclusions and recommendations of NASA's Comet Science Working Group (CSWG) concerning a first space mission to a comet.

A. OVERALL SCOPE AND OBJECTIVES OF COMET MISSIONS

Comets are probably the most primitive bodies remaining in our solar system and may preserve the clearest record of the chemical and physical processes which marked the beginning of the solar system 4.6 billion years ago. They may also be intimately connected with our terrestrial past. The influx of comets into the inner solar system may have affected the composition of the atmospheres of the terrestrial planets and may have provided the first input of organic molecules to the primitive Earth. Thus, the study of comets is an essential element in understanding the chemical and physical processes involved in the formation and evolution of our cosmic environment.

The three major scientific objectives of a space mission to a comet are, in order of priority:

(1) To determine the chemical nature and physical structure of comet nuclei, and to characterize the changes that occur as functions of time and orbital position.

(2) To characterize the chemical and physical nature of the atmospheres and ionospheres of comets as well as the processes that occur in them, and to characterize the development of the atmospheres and ionospheres as functions of time and orbital position.

(3) To determine the nature of comet tails and the processes by which they are formed, and to characterize the interaction of comets with the solar wind.

The CSWG recommends that a balanced payload which addresses all three major scientific objectives be selected for the first comet mission.

B. CONCERNING MISSION MODES

To address the major questions associated with Objectives (1) and (2), the first mission of a comet program must involve a rendezvous with the nucleus of a comet.

A stand-alone flyby mission cannot address Objective (1) and some key elements of Objective (2) in any significant way.

It is the opinion of the CSWG that although a lander/sample return mission is a prime candidate for a follow-on mission of the comet program, it is not an appropriate first mission because:

(1) Many first-order scientific questions concerning comets can be answered by a rendezvous mission and do not require a lander or a sample return. This is even true of questions concerning the nucleus (Objective 1).

(2) Our present knowledge of the nucleus and the near-nucleus environment is too poor to plan an optimum lander mission and to ensure a safe landing.

The scientific need for a rendezvous during the first comet mission underscores the need for a low, continuous thrust propulsion system.

C. CONCERNING THE FIRST MISSION OF A COMET PROGRAM

The CSWG concurs with the conclusions of its predecessor, the Comet Halley Science Working Group of 1977, that a rendezvous with Halley would have been the ideal first mission of a comet program. After reviewing the merits of the various options which remain open following NASA's decision not to seek a new start for the Halley rendezvous mission, we conclude that:

(1) A rendezvous is an essential element of a first comet mission, if this mission is to address the major science objectives in a significant manner.

(2) Of the comets with which a rendezvous can now be effected (Tempel 2, Encke, etc.), none show the full complement of cometary phenomena which are known to occur at Halley. Thus, although such a rendezvous is essential to achieve Objective (1), some aspects of Objectives (2) and (3) are compromised.

(3) An excellent alternative exists: a flyby of Halley on the way to a rendezvous with Tempel 2. The flyby of Halley imposes only a modest performance penalty on the trajectory to Tempel 2.

(4) A single-launch Halley Flyby/Tempel 2 Rendezvous mission has several important advantages:

   (a) It combines the intensive study of a comet nucleus and coma (at Tempel 2) with an investigation of the unique phenomena in the atmosphere of a very active comet (Halley).

   (b) It provides some comparative measurements for two very different types of comets.

Therefore, the CSWG recommends that the first mission of NASA's comet program be a Halley Flyby/Tempel 2 Rendezvous mission. The spacecraft can be launched in July 1985, fly by Halley in November 1985, and rendezvous with Tempel 2 in August 1988.

D. CONCERNING OTHER TARGETS

From its study, the CSWG concludes that:

(1) The two short-period comets, Tempel 2 and Encke, are the only suitable rendezvous targets for the next decade.

(2) On scientific grounds, Tempel 2 and Encke are of comparable interest and value. However, missions to Tempel 2 are significantly easier technically.

(3) No other short-period comets are suitable rendezvous targets. Candidates such as Tuttle-Giacobini-Kresak, Faye, and Honda-Mrkos-Pajdusakova are unsuitable scientifically and more difficult on technical grounds.

(4) There is no substitute for Halley. If we are to study a large active comet within our lifetimes, we must take advantage of the 1986 Halley opportunity. This comet will not return until 2061, and no comparable target is available before the 21st century.

E. CONCERNING OVERALL MISSION STRATEGY

1. Halley Flyby

To maximize the science return from the main spacecraft at Halley and to minimize the danger from dust, the CSWG recommends that the rendezvous spacecraft be targeted to pass approximately 10^5 km on the sunward side of Halley.

Since the rendezvous spacecraft cannot get close to the nucleus or inner coma of Halley, the CSWG recommends that a coma probe be deployed during the flyby and targeted directly at the nucleus. This probe should include protective dust shielding to ensure its survival to <1000 km from the nucleus.

It is not possible to target the rendezvous spacecraft to pass through the ion tail while avoiding dust hazards, and still fulfill prime science objectives of the Halley flyby. The CSWG feels that the scientific value of the mission would be enhanced enormously if an independently launched probe were to encounter the tail of Halley at the time that the coma probe and the rendezvous spacecraft are in the comet's vicinity. We recommend that NASA explore possibilities of international cooperation in this area.

2. Tempel 2

The CSWG recommends the following adaptive strategy during the rendezvous with Tempel 2:

(a) The spacecraft should arrive at Tempel 2 as long before perihelion as possible to maximize the duration of pre-perihelion observations.

(b) The spacecraft should make an exploratory close pass to within about 100 km of the nucleus before the time of maximum activity (predicted to occur about 20 days after perihelion).

(c) During the phase of maximum activity, the spacecraft should observe the comet from a minimum safe distance (about 1000 to 2000 km?).

(d) Before post-perihelion activity has subsided, the spacecraft should make several approaches to the nucleus to about 100 km to collect samples of cometary dust.

(e) As the comet settles into its post-perihelion quiescent state, the spacecraft should attempt to orbit the nucleus at a range of about 10 km.

(f) The mission should be terminated by an attempt at an experimental descent onto the nucleus.

Within these constraints, the CSWG recommends that a mission strategy be sought in which the rendezvous spacecraft makes an excursion anti-sunward of the nucleus to study tail phenomena of Tempel 2.

In order to study the nucleus in detail, some instruments require stay times of 100 to 150 days in close orbit. As this phase of the mission cannot begin until the comet's activity has died down (about 100 days after perihelion), the CSWG recommends that the minimum duration of the Tempel 2 rendezvous phase of the Halley/Tempel 2 mission be 1 year after rendezvous.

The CSWG urges that the mission be terminated by an attempt at an experimental descent onto the nucleus. The primary objective of this maneuver is to provide data on the mechanical properties of comet surfaces and on the hazards associated with a landing; such knowledge is essential in planning any future lander/sample return mission to a comet.

F. CONCERNING INSTRUMENTATION

The CSWG has identified an excellent set of candidate instruments which can fulfill the scientific objectives of the first comet mission (see Section IV of Part One; also see Part Two of this report). In some cases, only slight modifications to instruments that have flown on previous space missions are involved; others require special modifications or new developments.

Special attention should be given to:

(1) Evaluate effects of dust on the performance of mass spectrometers and design appropriate means of protection.

(2) Continue experimental tests to develop efficient dust collection surfaces.

(3) Improve techniques of determining the composition of collected dust samples.

(4) Design an imaging system which incorporates several focal lengths and provides wide spectral and dynamic ranges. Designs involving all-reflecting optics should be investigated to save weight and enhance the ultraviolet transmission characteristics of the system.

(5) Encourage the development of radar sounding instruments for studying the internal structure of the nucleus from the rendezvous spacecraft.

G. CONCERNING THE DUST ENVIRONMENT

The CSWG stresses that it is essential to have an improved assessment of the dust environment at both Halley and Tempel 2. For most scientific purposes one wants to get as close to the nucleus as possible, but safety considerations demand a more cautious strategy. At Tempel 2 a minimum stay of 1 month at $\lesssim$10 km from the nucleus is required, and a much longer period ($\sim$100 days) is desirable.

We urge that efforts continue to:

(1) Improve the models of the dust environments of Halley and Temple 2.

(2) Improve the models of the effects of this dust on the spacecraft and on the operation of the science instruments.

The CSWG also recommends continued investigations of techniques for operating a spacecraft adaptively in a constantly varying environment.

H. CONCERNING FOLLOW-ON MISSIONS

The CSWG has concluded that certain important and fundamental questions concerning comets and their relationship to the rest of the solar system can be answered only by direct laboratory measurements on returned cometary materials.

We believe that a sample return mission to a comet is an essential follow-on mission of a comet program, following the successful completion of the Halley Flyby/Tempel 2 Rendezvous mission described in this report.

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SECTION II

BACKGROUND

In January 1977, NASA formed the Comet Halley Science Working Group (CHSWG), headed by M. Belton, to consider the scientific merits of a rendezvous with comet Halley during its return in 1986. In its report (NASA TM-78420), the CHSWG '77 concluded that a rendezvous with Halley using low-thrust propulsion technology would be an ideal first mission of a comet program.

By January 1978, it became evident that the Halley Rendezvous mission would not obtain the required FY '79 new start. A new Comet Science Working Group was formed in 1978 to recommend an alternate first comet mission which could be achieved with an FY '81 new start. This group was headed by M. Belton, with S. Kumar serving as Study Scientist and Vice Chairman, and D. K. Yeomans as Executive Secretary. By this time, NASA had selected the ion drive (or Solar Electric Propulsion) as its low-thrust propulsion system. The 1978 CSWG held three meetings between January and May 1978, and presented its interim conclusions at the COMPLEX Summer Study on Comets and Small Bodies held in Snowmass, Colorado, in July 1978.

The working group was restructured into its present form in fall 1978. The present working group, the CSWG '79, developed its recommendations at four meetings between October 1978 and April 1979. These meetings were held:

On October 24 at the Jet Propulsion Laboratory (JPL).

On December 19, 20, 21 at Goddard Space Flight Center.

On January 25, 26 at JPL.

On April 24, 25 at JPL.

The present report summarizes the conclusions and recommendations reached during these deliberations and also draws heavily on the work of the 1978 Comet Science Working Group. Important related material is contained in the report of the CHSWG '77 (NASA TM-78420).

The members of the CSWG '79 were:

Joseph Veverka (Chair)	Cornell University
Marcia Neugebauer (Vice Chair and Study Scientist)	Jet Propulsion Laboratory
James R. Arnold	University of California, San Diego
Michael J. S. Belton	Kitt Peak National Observatory

Jean-Loup Bertaux	Service d'Aeronomie du CNRS
John C. Brandt	Goddard Space Flight Center
Donald E. Brownlee	California Institute of Technology
Benton C. Clark	Martin Marietta
Armand H. Delsemme	University of Toledo
Donald M. Hunten	University of Arizona
H. Uwe Keller	Max Planck Institut für Aeronomie
Jochen Kissel	Max Planck Institut für Kernphysik
Konrad Mauersberger	University of Minnesota
David Morrison	University of Hawaii
Andrew F. Nagy	University of Michigan
Ray L. Newburn, Jr.	Jet Propulsion Laboratory
Hasso B. Niemann	Goddard Space Flight Center
Tobias Owen	SUNY Stony Brook
Frederick L. Scarf	TRW
Zdenek Sekanina	Smithsonian Astrophysical Observatory
Gary E. Thomas	University of Colorado
Leonard Tyler	Stanford University
George W. Wetherill	Carnegie Institution of Washington
Laurel L. Wilkening	University of Arizona
John A. Wood	Smithsonian Astrophysical Observatory
Donald K. Yeomans (Executive Secretary)	Jet Propulsion Laboratory

The advisors and consultants of the CSWG '79 were:

Kenneth L. Atkins	Jet Propulsion Laboratory
Leonard F. Burlaga	Goddard Space Flight Center
G. Edward Danielson	California Institute of Technology
Merton Davies	Rand Corporation

Charles Elachi	Jet Propulsion Laboratory
Nancy Evans	Jet Propulsion Laboratory
Crofton B. Farmer	Jet Propulsion Laboratory
Hugo Fechtig	Max Planck Institut für Kernphysik
Martha Hanner	Jet Propulsion Laboratory
Daniel H. Herman	NASA Headquarters
Wesley Huntress	Jet Propulsion Laboratory
Hugh Kieffer	USGS (Flagstaff)
Robert E. Murphy	NASA Headquarters
John Oro	University of Houston
Elizabeth Roemer	University of Arizona
Bradford A. Smith	University of Arizona
John Wasson	University of California, Los Angeles
Fred L. Whipple	Smithsonian Astrophysical Observatory

Much of the group's work was achieved by various subcommittees. The principal subcommittees and their members were:

(1) Plasma Physics. Scarf (Chair), Brandt, Keller, Nagy, and Neugebauer; Burlaga (Advisor).

(2) Mass Spectrometry. Nagy/Neugebauer (Co-Chair), Delsemme, Keller, Mauersberger, Niemann, and Wetherill; Huntress (Advisor).

(3) Imaging. Belton (Chair), Brandt, Delsemme, Morrison, Newburn, Owen, Sekanina, Veverka, and Wood; Danielson, Davies, Evans, and Smith (Advisors).

(4) Remote Sensing of the Atmosphere. Hunten (Chair), Bertaux and Thomas; Farmer, Kieffer, and Taylor (Advisors).

(5) Dust and Solids Investigations. Wilkening (Chair), Arnold, Brownlee, Clark, Kissel, Sekanina and Wood; Fechtig, Hanner, Oro, Wasson, and Whipple (Advisors).

(6) Remote Sensing of the Nucleus. Morrison (Chair), Arnold, Brandt, Newburn, Sekanina, Wilkening, and Wood; Hanner, Kieffer, Wasson, and Whipple (Advisors).

(7) Mass Determination, Radar, and Radio Science. Wetherill (Chair), Tyler, Veverka and Yeomans: Elachi (Advisor)

(8) Probe Science. Scarf (Chair), Belton, Bertaux, Brandt, Keller, Kissel, Mauersberger, Nagy, Neugebauer, Sekanina, and Veverka.

The Charter of the Comet Science Working Group 1979 was to:

(1) Develop the scientific objectives of a first comet mission.

(2) Select mission targets and the optimum strategy for this mission.

(3) Recommend a science payload and assess the availability and state of development of the different instruments and techniques required.

(4) Briefly consider possible follow-on missions of the comet program.

The main work in the instrument area (requirements, state of development, etc.) was carried out by the instrument subgroups listed above. Significant developments in several key instrument areas (dust collection, operation of mass spectrometers in a dusty environment; new design for an imaging system) got underway during the lifetimes of the CSWG '78 and '79.

Considerable progress was also achieved in establishing a Comet Observing Program to obtain much needed telescopic observations of those comets which are possible candidates for early missions within NASA's program of comet exploration. The Comet Observing Program was administered by a subcommittee of the CWSG '79 consisting of: R. Newburn (Chair); E. Roemer and F. L. Whipple (Advisors).

SECTION III

SCIENTIFIC RATIONALE AND OBJECTIVES

A. INTRODUCTION

A major objective of NASA's program of space exploration is to deepen man's understanding of the origin and evolution of his cosmic environment. The past decade has witnessed the initial stages of a spectacularly successful program of planetary exploration. However, planets and their satellites retain at best a blurred record of their births, obscured by billions of years of evolution during which complex processes have reshaped their interiors and surfaces. By contrast, comets are among the most primitive objects remaining in our solar system. Because of their minute size and the fact that they have spent most of their existence deep-frozen on the fringes of the solar system, comets are expected to preserve the chemical and physical characteristics with which they were formed.

What do we know about these messengers from the distant past? In this short report, we can only summarize some of the principal observed features and theories about comets. Much more detail can be found in the following highly recommended reviews and collections of original papers: (1) F. L. Whipple and W. F. Huebner, Annual Reviews of Astronomy and Astrophysics, Vol. 14, p. 143, 1976; (2) Comet Kohoutek, edited by G. A. Gary, NASA SP-355, 1975; and (3) The Study of Comets, edited by B. Donn et al., NASA SP-393, 1976.

The heart of a comet is its nucleus—a solid body thought to consist of a mixture of ices (mainly water) and other volatile molecules built of H, C, N, and O, and of rocky material. The degree of compaction and the strength of the rocky material is not known, although some fraction exists as fine grains of dust, and the overall structure may be very weak. The dimensions and mass of most cometary nuclei are inferred to be in the range from 1 to 10 km and from 10^{15} to 10^{18} g, respectively. As a result, the gravitational attraction, or equivalently the escape velocity (1 to 5 m/s), is tiny in comparison to that of planets, and any gases evaporated from the surface quickly escape.

Our knowledge of comets comes from observations of their activity as they approach the sun. Heated by solar radiation, the nucleus releases large amounts of gas and dust during its passage through perihelion. This unpredictable and occasionally violent process produces a very tenuous atmosphere of enormous extent. Neutral molecules, some highly reactive, are formed by sublimation and probably other processes occurring very close ($< 10^3$ km) to the nucleus and then expand to distances of 10^5 to 10^7 km. Occasionally, one observes capricious bursts of activity in the form of jets and halos. Some of the neutral molecules become ionized surprisingly close to the nucleus by processes which are poorly understood. The ions are subsequently accelerated out of the central region to form the plasma tail. These plasma or ion tails show visual evidence of complex hydromagnetic phenomena (filaments, rays,

kinks, and helices) and attain lengths of about 1 AU in some comets. The acceleration of the tail ions and the complex tail structures are evidently related to the flow of solar wind past the comet.

The gas streaming from the nucleus carries with it quantities of fine dust, which is often responsible for much of the visual brightness of a comet. As a result of solar radiation pressure, the dust particle trajectories bend away from the sunward direction at about 10^4 km from the nucleus, sweeping back to form a long, curved dust tail. Figure 1-1 summarizes these phenomena. The great variety of scale sizes of the phenomena displayed by a bright, active comet is shown in Figure 1-2.

The orbital properties of comets show that they belong to the solar system. It is estimated that about 10^{11} comets exist in a vast cloud around the sun, with a total mass perhaps greater than the mass of the Earth. For reasons not yet understood, this material did not form a single large planet, but remained dispersed in very small bodies within which the internal pressure and temperature were presumably not sufficient to cause differentiation or other significant physical changes. Thus, comets are probably the most pristine objects available for study in the solar system.

It is believed that comets spend almost their entire lives on the fringes of the solar system beyond the orbits of the planets, out of reach of the sun's heat. Only when random stellar perturbations drop a comet into the inner solar system does a comet begin its brief period of spectacular activity and rapid progress toward extinction. In its first few passages close to the sun, the "fresh" comet releases pristine surface volatiles at a spectacular rate. Most of the very bright comets recorded over the past several millennia are in this category. Unfortunately, the time and place of appearance of such "fresh" comets cannot be predicted, and their orbits are generally of high eccentricity and inclination. Thus, such comets are not feasible targets for spacecraft exploration. Occasionally, a "fresh" comet passes close to Jupiter or Saturn during its excursion into the inner solar system and is deflected into a tighter orbit about the sun. After several such planetary encounters, the comet can evolve into a short-period orbit to become a periodic comet. Typically, it loses up to 1 percent of its mass at each perihelion passage and may survive only a few hundred orbits before its volatiles are exhausted. Comet Halley is unique as the only periodic comet that is still large enough and young enough to display the full range of phenomena associated with new comets.

As a periodic comet ages, its level of activity declines, and presumably its ratio of solids to ices increases. Several such evolving comets, including Encke and Tempel 2, are in orbits that are accessible to spacecraft investigation. Ultimately, when the volatiles are depleted, the rocky residue of a comet may become an Apollo/Amor asteroid, or it may disperse and disappear entirely.

Chemically, comets offer the apparent paradox of combining both oxidized and reduced constituents. In their spectra, we find evidence

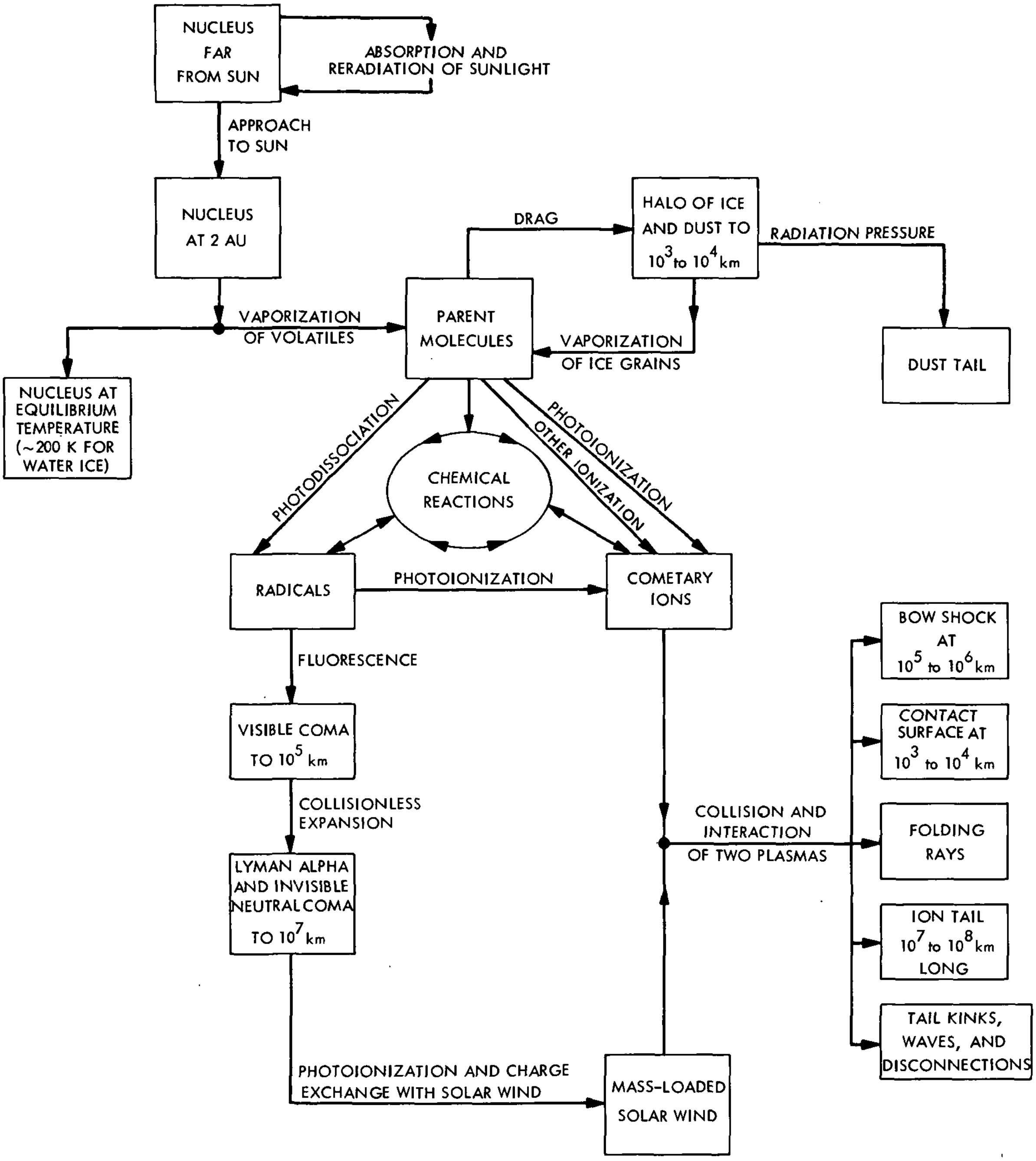

Figure 1-1. Features and Processes Involved in the Interaction of a Comet with Sunlight and the Solar Wind

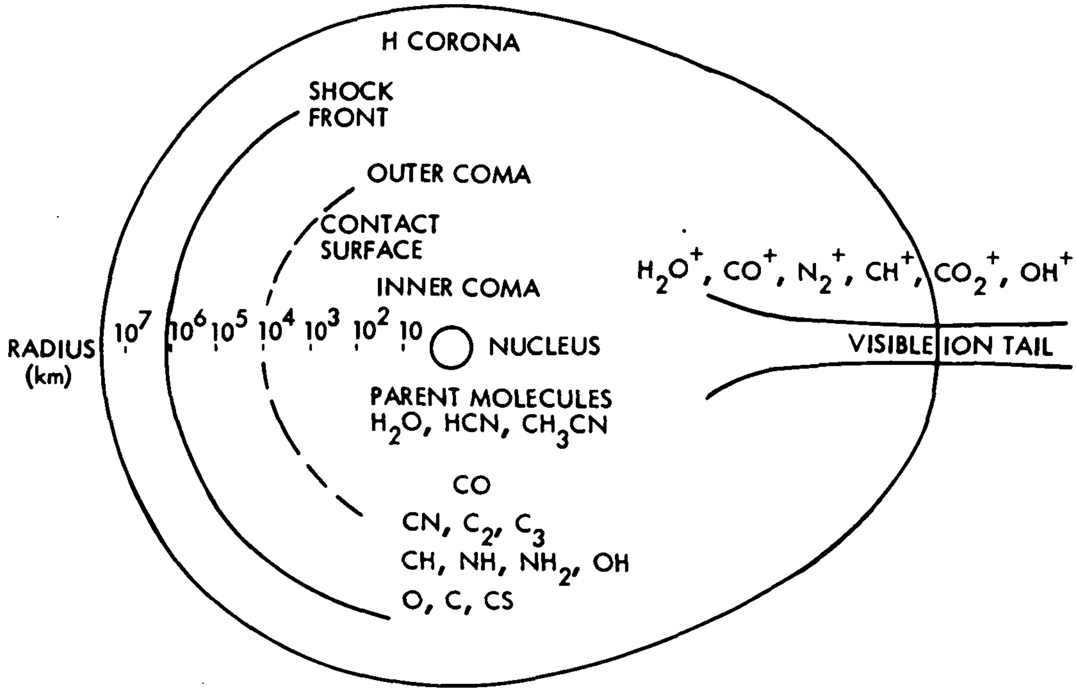

Figure 1-2a. **Sketch of Principal Gaseous Features of a Typical Comet on a Logarithmic Scale**

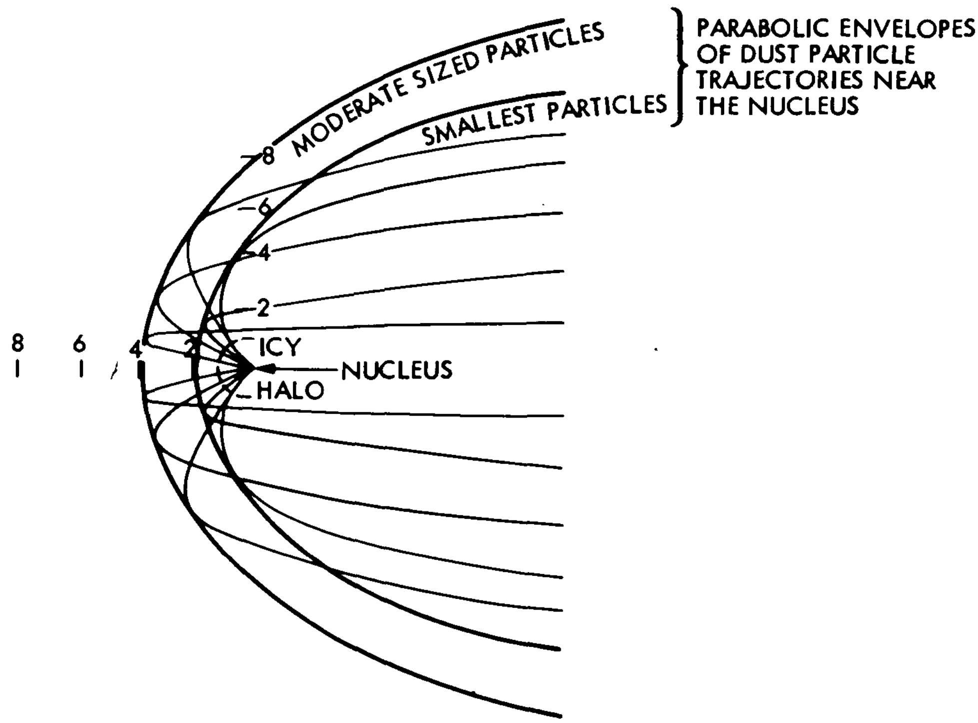

Figure 1-2b. **Sketch of Principal Particulate Features of a Typical Comet on a Linear Scale. Units 10^4 km**

of CO_2 and CH, and of NH_2 and N_2. If comets play an important part in delivering volatile material to the surfaces of the inner planets, as has been suggested, then a study of their composition should provide useful clues about the nature of the prebiological chemical environment on the Earth.

One theory holds that comets formed in a spherical halo on the outer fringes of the solar system out of nebular material which had never been heated to temperatures high enough to melt interstellar dust grains and their icy mantles. Thus, comets could contain valuable information about the processes that led to the formation of these grains in the parent interstellar clouds and elsewhere.

Another view holds that comets formed in the disk of the preplanetary nebula in the vicinity of the outer planets, and were then gravitationally scattered to their present configuration. In this view, comets may be samples of the "building blocks" or planetesimals from which Uranus and Neptune were constructed. If this is the case, we may expect that their study will yield new information on the degree of chemical disequilibrium, the physical state, the heterogeneity, and mixing processes in the primitive nebula at the time and place they were formed. Thus, the study of comets may provide insights into the processes of agglomeration and formation of planetesimals in the solar nebula.

A knowledge of the chemical composition of comets is also critical in establishing their origin and their role in other aspects of cosmic chemistry. There is a general feeling that there is a continuity of relationships involving the large organic molecules found in dense interstellar clouds, the formation of planetary systems, the origin of comets and meteorites, and the delivery of carbon, nitrogen, and water and other volatiles to the surface of the primitive Earth. The discovery of amino acids in some carbonaceous chondrites, the presence of the C_3 radical in comet spectra, and the apparent existence of HCN and CH_3CN in both the interstellar medium and comets are parts of this puzzle. Nevertheless, these relationships will remain vague until we have more precise information: What is the chemical state of a comet nucleus? What are the mysterious parent molecules whose fragments we see in comet spectra? Were they formed in the interstellar medium, or are they local products of the solar system? What are the abundances of noble gases and other volatile elements? Are the dust grains in comets the same type as the grains that produce the interstellar extinction? Is there evidence that they have played a critical role in molecule formation? It is possible to generate a virtually endless list of such questions, and although we will not answer all of them directly with experiments on the first comet mission, we should be able to obtain some deep insights. For example, we can expect a clarification of the nature of parent molecules and their relation to molecules found in interstellar space; a clarification of the processes by which cometary nuclei evolve and provide the awesome displays witnessed from Earth; and a clarification of their relationship to other matter in the solar system, such as meteorites, meteoroids, asteroids, and the interplanetary dust.

The various physical and chemical processes taking place in comets are also of great interest. The cometary atmosphere is so tenuous that the physical conditions there cannot be simulated in the laboratory. Like the extreme upper atmospheres of the planets, the gas envelope of comets exists in an unfamiliar state in which atoms collide infrequently and can emit radiation forbidden in less extreme conditions. It is also the state in which complicated plasma-physical processes often dominate more familiar forces. In a comet mission, we can expect by direct measurement to learn about chemical reactions and dissociation and excitation processes which have applications to more general problems of understanding both diffuse interstellar clouds and planetary atmospheres. We can also explore plasma-neutral and plasma-plasma interactions in the unique environment of an essentially massless obstacle to the solar wind flow.

It has been argued that the influx of cometary material over 4.6 billion years has significantly affected the chemical composition of the atmospheres of the terrestrial planets—including our own. Furthermore, comets may have provided the first influx of complex organic molecules to the primitive Earth. Are we all descended from comets which brought the elements vital for life to the surface of the Earth in ancient times? This thought is an arresting one. The fact that we can ask such a question is a good indication of why we are so interested in these objects and how little we really know about the early history of our own planet.

In the final analysis, we also need to visit one or more comets as a simple act of exploration. Comets are an important aspect of our solar system. Yet the small size of cometary nuclei makes it virtually impossible to answer fundamental questions from observations made on Earth or in Earth orbit. A comet mission is required to complete the first-order reconnaissance of our solar system environment.

B. SCIENTIFIC OBJECTIVES FOR A PROGRAM OF COMET EXPLORATION

In the broadest possible terms, a program of comet exploration should address the following objectives:

(1) To determine the chemical nature and physical structure of comet nuclei, and to characterize the changes that occur as functions of time and orbital position.

(2) To characterize the chemical and physical nature of the atmospheres and ionospheres of comets as well as the processes that occur in them, and to characterize the development of the atmospheres and ionospheres as functions of time and orbital position.

(3) To determine the nature of comet tails and of the processes by which they are formed, and to characterize the interaction of comets with the solar wind.

These objectives, based on the deliberations of the CSWG '79, are listed in order of priority; however, the CSWG strongly believes that a first comet mission should address all three objectives as part of a balanced program. These objectives are related to a host of scientific questions about comets and about their relationship to the rest of the universe, some of which are outlined in Table 1-1.

C. SCIENTIFIC MERIT OF DIFFERENT MISSION OPTIONS

The Comet Halley Science Working Group, in its report, considered the relative merits of four types of cometary missions: (1) flybys, (2) rendezvous, (3) landers, and (4) sample returns. These options are discussed below.

(1) Flyby missions are characterized by a high relative velocity (>1 km/s) between the comet and the spacecraft and allow only a brief period of useful observing (generally $<10^4$ s), with limited opportunities for studying the nucleus.

(2) Rendezvous missions are characterized by very low velocities (<1 m/s) relative to the comet with the capability for maneuvering near the nucleus for extended periods of time (many months). They have the flexibility to explore the spatial and temporal dimensions of a comet as it sweeps through the inner solar system and to respond to changing degrees of hazard from cometary dust. Remote sensing techniques can be used for detailed studies of the nucleus in combination with in situ analyses of gases and dust in the coma.

(3) A lander that could operate on the surface of the nucleus would allow direct examination of its structure. Close-up imaging would reveal the degree of aggregation and the physical relationship of solids and ice. Elaborate chemical analysis of solids and ices becomes possible by several different techniques to provide information about the mysterious parent molecules and to establish whether a physical link exists between comets and meteorites.

(4) A sample return allows many types of material analysis that are too complex to be handled remotely. These types include radiometric dating and most other isotopic studies, detailed mineralogical analysis of silicates, some studies of organics, and mineralogic evidence of the thermal history of the silicate components. Any link with meteorites can be unambiguously confirmed.

The CHSWG concluded that a lander or sample return mission was not an ideal first mission of a comet program for at least four reasons:

(1) Our present knowledge of the nucleus and of the near-nucleus environment is too vague to ensure that the practical details of such a mission could be carried out successfully.

Table 1-1. General Scientific Questions and Measurement Objectives That Can be Addressed on a First Comet Mission

Scientific Objective	Scientific Questions or Measurement Objectives
General scientific questions	When and where do comets form?
	What were the pressure and temperature conditions at which comets formed?
	How did the processes of condensation and agglomeration occur?
	Do comets contain any evidence of large-scale mixing in the solar nebula?
	What can comets tell us about interstellar gas and dust?
	Can we establish a firm physical link between cometary solids and certain classes of meteoritic material?
	Can we establish a link between cometary nuclei and the asteroids?
	What can we learn about the contribution of comets to planetary volatiles?
(1) Determine the chemical nature and physical structure of comet nuclei. . .	What are the mass and density of the cometary nucleus?
	What are the size, shape, and state of rotation of the nucleus?
	How homogeneous is the physical and chemical structure of the nucleus?
	What are the albedo, color, and photometric and electrical properties of both the nucleus and its units?
	What is the surface temperature and energy balance of the nucleus?
	What is the elemental composition of the nucleus and what are its major volatile, refractory, and siderophile species?
	What is the interior structure of the nucleus?

Table 1-1. (Cont'd)

Scientific Objective	Scientific Questions or Measurement Objectives
. . . and characterize the changes that occur as functions of time and orbital position	What causes "activity" on the nucleus? Is activity a surface or a subsurface phenomenon? How much material is lost by the comet during perihelion passage? How is it ejected from the nucleus? Does it come from specific places?
(2) Characterize the chemical and physical nature of the atmospheres and ionospheres of comets as well as the processes that occur in them. . .	What are the abundances of the different molecules and ions making up the cometary atmosphere? What are the velocity distributions of neutral and ionic species and electrons? Is there a collision zone in which gas-phase chemical reactions take place near the nucleus? What are the "parent" molecules? What are the dominant ionization mechanisms? Are they steady or transient? What happens to the "parent" molecules in the atmosphere? What are the "jets", rays", "halos" and "envelopes" seen from the ground? What is the gas-to-dust mass ratio? What are the chemical composition and physical structure of the dust grains? Do "icy" grains exist? What is their lifetime?
. . . and characterize the development of the atmospheres and ionospheres as functions of time and orbital position	What are the time dependences of the above phenomena? For example, what is the production rate of cometary gases and how does it vary? What is the size distribution and flux of dust in the comet's atmosphere?

Table 1-1. (Cont'd)

Scientific Objective	Scientific Questions or Measurement Objectives
	What is the production rate of dust? What are the physical and chemical structures of the gas and dust envelopes (scale heights, time constants, etc.)?
(3) Determine the nature of comet tails and of the processes by which they are formed, and characterize the interaction of comets with the solar wind	What is the physical nature of tail phenomena observed from the ground? How does disconnection occur? How does a new tail form? What are the excitation, dissociation, and ionization processes? What insight can we gain from cometary phenomena about energetic geomagnetic and astrophysical phenomena? Is there a well-defined bow shock? Where is it? What is its physical character? Does mass loading lead to a diffuse or extended shock? Is there a contact surface? Where is it? What is its physical character? How are solar-wind energy and momentum transferred to the tail? How are ions accelerated into the tail? Does the comet capture and amplify the magnetic field in the solar wind? What role do wave motions and dissipation play in production of ionization and tail phenomena? Are large electric currents induced in the cometary atmosphere? What are the "filaments" and "motions" seen in the plasma tail? Are there high-energy particles? What is their role in ionization mechanisms?

(2) For the same reason, we cannot at present refine our scientific questions precisely enough to maximize the science return from such a mission.

(3) Many of the important first-order scientific questions concerning comets (see Table 1-1) can be achieved by a rendezvous mission and do <u>not</u> require a lander or a sample return.

(4) For practical considerations, a lander or sample return is judged as too ambitious for the first mission of a comet program.

The CHSWG also concluded that a flyby was inadequate as a first mission, primarily because of its very limited ability to study the nucleus (Objective 1) and also because of the "snapshot" nature of this type of exploration. The CHSWG, therefore, concluded that the first comet mission should be a rendezvous mission. The CSWG '79 fully agrees with and supports this conclusion.

It is true that the full attainment of Objective (1) requires both remote sensing and direct sampling of the nucleus. Nevertheless, we are of the opinion that a major part of Objective (1) can be achieved with present generation instruments during a close rendezvous. In contrast, we believe that flyby missions do not have the capability of addressing Objective (1), the prime objective of any comet program, in any significant way.

Objective (3) requires special consideration, for although we are satisfied that a powerful instrumental capability exists for making the necessary measurements, the phenomena associated with the comet tail are often so rapid (time scales of hours) and exist over such an enormous range of sizes (distance scales of 10^2 to 10^6 km) that instruments on a single spacecraft at rendezvous are not adequate to properly characterize all the processes taking place (Section IV-E).

It is important to realize that the attainment of Objectives (2) and (3) requires extended observations of the cometary nucleus, atmosphere, and ionosphere at a range of distances from the nucleus and from the sun. The requirement for long integration times emphasizes the basic strength of rendezvous missions over flyby missions in these areas.

In order to achieve rendezvous with a comet, a continuous low-thrust propulsion system is required. Without an advanced propulsion system, there can be no rendezvous; and without a rendezvous, many of the major science objectives of a comet program cannot be addressed.

D. SELECTION OF A COMET FOR A FIRST COMET MISSION

The process of selecting an ideal candidate target for a first comet mission was begun by the CHSWG in 1977. We agree with that group that an optimum candidate for the first cometary mission should fulfill three criteria. One wants:

(1) A comet with a reliable orbit that is well known years in advance.

(2) A moderately bright comet whose behavior can be predicted with confidence and which is known to exhibit a broad range of cometary phenomena.

(3) A "fresh" comet whose properties have been only slightly changed by the environment of the inner solar system.

The first and third criteria are contradictory. The first criterion is necessary for mission planning; it restricts the choice to short- and intermediate-period comets.

We agree with the conclusions of the CHSWG that:

> "Given the capability to perform a rendezvous mission with a high inclination comet, Comet Halley clearly stands out as the best candidate."

In fact, Halley is the <u>only</u> comet with a predictable orbit which can be studied this century and which is active enough to display the full range of known cometary phenomena.

We also agree with the conclusions of the CHSWG that to achieve most of the scientific objectives of a first comet mission, and more specifically to address the prime objective, the characterization of the nature of the nucleus, a rendezvous is absolutely essential.

In its deliberations during the past year, the CSWG has reached the following conclusions concerning the optimum first mission needed to achieve the scientific objectives outlined in Section III-C:

(1) Certain cometary phenomena are known to occur only in large, very active comets. Most of the science objectives of a first comet mission could be achieved by a rendezvous mission to such a comet.

(2) Stand-alone flyby missions, even of bright, active comets, cannot address these objectives in sufficient detail. This statement is especially true insofar as studies of the nucleus and of time-dependent phenomena are concerned.

(3) Missions to bright and active comets involve at least three basic difficulties:

(a) The apparitions of most such comets are unpredictable.

(b) In most instances, the time interval between discovery and perihelion passage is too short to permit the planning and execution of a mission.

(c) As most of these comets have not been seen before, their activity as a function of time cannot be predicted (another mission hazard).

(4) Comet Halley, due to return in 1985-1986, is a unique bright, active comet to which we could plan a rendezvous mission.

We agree with the conclusions of the CHSWG that a rendezvous with Halley would achieve a large number of the essential scientific objectives and would have been the ideal first mission of a comprehensive comet program. As NASA has chosen not to carry out this mission, a decision which for practical reasons is now irrevocable, the CSWG has searched for an alternate first mission—one which does not involve a <u>rendezvous</u> with Halley.

Our study has shown that:

(1) A rendezvous is an essential element of a first comet mission, if this mission is to address the major scientific objectives in a significant manner.

(2) Of the comets with which a rendezvous can be achieved (Tempel 2, Encke, etc.), none shows the full complement of cometary phenomena that Halley is known to possess. Thus, while such a rendezvous would be excellent in terms of Objective (1), some aspects of Objectives (2) and (3) would be compromised.

Fortunately, the CSWG has found that an attractive alternative exists — a flyby of Comet Halley on the way to a rendezvous with the nucleus of the short-period comet Tempel 2. The flyby of Halley imposes only a modest performance penalty on the trajectory to Tempel 2, and the rendezvous spacecraft could drop off a dedicated probe at Halley to study this active comet in more detail. Such a mission has many advantages; for example:

(1) It provides for an extended rendezvous phase at Tempel 2 during which Objectives (1) and (2) could be addressed.

(2) It provides the opportunity during the Halley flyby phase to study the unique phenomena in the atmosphere of an active comet.

(3) It provides for comparison of two very different comets (Table 1-2).

Table 1-2. Observed Characteristics of Comets Halley and Tempel 2

	Halley	Tempel 2
	Observed	
Earliest recorded apparition	87 B.C.	1873 A.D.
Number of observed apparitions	27	16
Period	76 years (approx)	5.3 years
Orbital inclination (with respect to ecliptic)	162 deg	12 deg
Perihelion distance	0.6 AU	1.4 AU
Absolute total magnitude (approximate)	5	10
Photometric behavior	• Brighter post-perihelion • Fountain effect from nucleus sunward • Spherical halos expanding from nucleus (0.1 to several km/s) • Jets and streamers showing evidence for directed ejection • Explosive outbursts • Maximum visual coma diameter: $\sim 4 \times 10^5$ km	• Rapid brightness increase begins 80 days before perihelion; more gentle brightness decrease post-perihelion (see Figure 1-4) • Sunward fan-shaped coma suggests anisotropic outgassing • Maximum visual coma diameter: $\sim 1 \times 10^5$ km
Spectroscopic data	• CN, C_2, C_3, CO^+, N_2^+ Strong continuum • $^{12}C^{13}C$ isotopic bands in the Swan system of C_2 molecule	• CN, C_2, C_3, CO^+ Strong continuum
Tail structure	• Dust tail and ion tail present • Motion of fine streamers and disconnection phenomena in ion tail • Numerous envelopes showing "closing umbrella" phenomena • Maximum visual tail length $\sim$0.75 AU reached 5 to 6 weeks post-perihelion • Ion tail begins to form $\sim$ 1.5 AU pre-perihelion. Dust tail begins to form near perihelion	• No observed tail; however, the CO^+ emission of the normal onset of an ion tail is observed in the coma region
Meteor shower attributed to cometary debris	• η Aquarid (early May) Orionid (late October)	• None (cannot be observed because perihelion distance is well outside Earth's orbit)
	Calculated	
Radius	2.5 km	1.5 km
Production rate, molecules/s	7×10^{29} (peak) 4×10^{28} (at flyby)	7×10^{25} (at rendezvous) 1×10^{27} (peak)

The last point deserves emphasis: Some measurements made during the flyby of Halley, and especially those that could be obtained by a coma probe, could be compared directly with those obtained at Tempel 2. Thus, we can compare a snapshot of a large, active comet with a detailed study of a typical, much less active short-period comet. Also, it seems that Halley and Tempel 2 are representative examples of young and old comets in the evolutionary sequence.

Among the 72 comets that have been seen at least twice, Halley is the brightest and has one of the longest periods, whereas Tempel 2 is significantly fainter and has one of the shortest periods. All comets fade rapidly in luminosity over centuries because they lose volatiles and split frequently. Because of planetary perturbations, there also is a random walk in the binding energy of their orbits. As this random walk constantly ejects comets out of the solar system, the remaining comets are, as a group, on shorter-period orbits as they grow older.

The two parameters, "brightness" and "binding energy," are correlated only statistically. However, they both suggest that Halley is "young" and that Tempel 2 is "old" in the evolutionary sequence. The choice of these two comets seems, therefore, especially appropriate for investigation in a first comet mission.

The choice of Tempel 2 as the rendezvous comet is justified in the following section. However, the unique role of Halley in this scenario cannot be understated. If we want to study a large, active comet, Halley is the only choice. <u>Halley will be here in 1986 and will not return until 2061!</u>

E. ALTERNATIVE MISSION OPTIONS

The CSWG concludes that the baseline mission outlined in Section III-D, a flyby of Comet Halley followed by a rendezvous with Tempel 2, is the optimum mission choice available to us, and that no alternative exists which is competitive with it either in scientific value or in cost effectiveness.

The most nearly acceptable alternative to this baseline mission would be a dual-launch program that achieves separately the two fundamental goals of the baseline, namely a flyby of Halley and a rendezvous with Tempel 2. We note, however, that some scenarios for such a dual-launch program yield substantially inferior remote sensing of Halley and a serious degradation of the capability to deliver a spacecraft to regions of the neutral atmosphere near the nucleus of Halley. Furthermore, one would expect that the dual-launch program would be considerably more expensive than the baseline if it were to accomplish the same science. Another alternative would be to forego Halley entirely and carry out only a rendezvous with a short-period comet, such as Tempel 2 or Encke. Although still of great scientific value, such a mission loses most of the vital elements associated with observations of a large, active comet which uniquely displays the full range of cometary phenomena.

Any alternative mission, including the dual launch to effect a Halley flyby and a Tempel 2 rendezvous, would require considerable further study. The CSWG did not have time to consider what changes in the science payloads and mission strategy would be needed.

The position expressed concerning the outstanding merits of the Halley/Tempel 2 opportunity is based on a 2-year study by the CSWG of various mission opportunities available during the next 15 years. Preliminary results of this study were reported in JPL Document 78-55 entitled Mission to Comets: An Options Review compiled by K. Atkins in July 1978. Five candidates for rendezvous comet missions were identified through 1993:

(1) Tempel 2 (1988).

(2) Tuttle-Giacobini-Kresak (1990).

(3) Encke (1990).

(4) Honda-Mrkos-Pajdusakova (1990).

(5) Faye (1991).

Missing from this list is a 1987 Encke opportunity, which would require a launch even earlier than the Tempel 2 opportunity (see below).

When a rendezvous mission to each of the above five comets is combined with an en route flyby of comet Halley, only the Tempel 2 and Encke opportunities provide a reasonable option for probe deployment at Halley using a single launch. The remaining three opportunities not only have the disadvantage that they cannot easily be combined with a probe deployment at Halley, but in addition, involve comets of inferior scientific potential compared to either Tempel 2 or Encke. The basic problem with these comets is that they are significantly fainter; hence, the maximum gas production rates are much lower, and the likely range of observable phenomena is more restricted. In addition, comet Tuttle-Giacobini-Kresak displays in its activity large, erratic, and unpredictable variations, which represents an unacceptable mission hazard. Finally, missions to these other comets are more difficult (in terms of power, etc.) than the 1988 Tempel 2 opportunity.

The CSWG considered in detail the relative merits of Tempel 2 versus Encke as rendezvous targets, and concluded that they were of comparable scientific potential. The maximum expected gas production rates of the two comets are similar at the same distance from the sun, about 1 to 5 x 10^{27} molecules per second at 1.4 AU. (For comparison, the rate is about 20 times higher for Halley at 1.4 AU.) The nuclear region of Tempel 2 is slightly brighter (by about 0.5 magnitude) but, given the uncertainty in comet albedos, one can only conclude that both nuclei have radii between about 0.5 and 2.0 km. Encke is intrinsically fainter after perihelion than before, has a small ion tail, and a spectrum which lacks a continuum. Tempel 2 is intrinsically brighter after perihelion,

lacks a tail, and does show a strong continuum. Both comets have similar maximum visual coma diameters (2×10^5 km), and the comas of both exhibit a sunward fan indicative of localized activity on the nuclei. (A detailed model of Tempel 2 has been published by R. Newburn as JPL Publication 79-60.) Neither comet provides a good opportunity to study plasma-tail phenomena, one fundamental reason why a combined mission involving a flyby of Halley is so attractive in terms of total science return.

Although the CSWG concluded that, in terms of science, Tempel 2 and Encke are equally attractive rendezvous targets, engineering studies at JPL have demonstrated that, from a technical point of view, Tempel 2 is a much easier target.

Of the two Encke opportunities (1987 and 1990) that could be combined with a flyby of Halley, we have not considered seriously the 1987 opportunity because it would involve an <u>earlier</u> launch than the Halley/Tempel 2 mission (March 1985, compared to July 1985) and imposes greater power requirements than the 1990 Encke opportunity. Although feasible, the Halley/Encke 1990 mission is technically much more difficult than the Halley/Tempel 2 1988 mission, and its scientific return would be less because the science payload would have to be smaller and the instruments would have to operate under severe thermal conditions.

The CSWG concluded that Tempel 2 is the optimum rendezvous candidata for a mission combining a flyby of Halley with a rendezvous with a short-period comet.

SECTION IV

INSTRUMENT CAPABILITIES FOR A COMET MISSION

A. INTRODUCTION

The CSWG has considered optimal instrument payloads for the Halley Flyby/Tempel 2 Rendezvous mission outlined in Section III. The task of examining in detail what measurements are implied by the science objectives and what instruments are required to carry out such measurements was undertaken by seven Subgroups whose full reports appear in Part Two of this document. This section summarizes the recommendations of these Subgroups and uses them to construct model payloads for both the rendezvous and coma probe spacecraft. A specific duty of each Subgroup was to assess the degree to which suitable instruments already exist in its particular area, and to identify any key developments that must be undertaken immediately to ensure that the requisite instruments are available for the first comet mission.

The typical payloads discussed below should serve only as examples and contain only those instruments which the Subgroups felt would be ready for the 1985 launch of the Halley/Tempel 2 mission.

B. TYPICAL PAYLOAD AND MEASUREMENT OBJECTIVES: RENDEZVOUS

Table 1-3 lists the instruments that we consider should be included as part of a typical instrument payload on the rendezvous spacecraft and gives estimates of the mass, power, and data rate. A range of values is given because of uncertainties in the available mass estimates. The bottom part of Table 1-3 includes some instruments that should be included in the rendezvous spacecraft payload if development work is satisfactorily completed and/or if the extra mass can be accommodated.

Table 1-4 indicates the primary measurement objectives and anticipated capabilities of the instruments in Table 1-3. In cases in which there is more than one appropriate instrument, each is discussed separately; e.g., infrared and millimeter-wave radiometers. The relationship between the suggested instruments and the scientific objectives is shown in Table 1-5.

C. GENERAL CHARACTERISTICS OF THE RENDEZVOUS PAYLOAD

1. Mass Spectrometry

The abundances of volatile species in the coma of Tempel 2 can be measured with slightly modified versions of available flight mass spectrometers. Special attention must be paid to the outgassing of adsorbed

Table 1-3. Scientific Instruments for Rendezvous Spacecraft

Instrument	Mass Range, kg	Power, W	Date Rate, kb/s
Typical Payload			
1. Neutral mass spectrometer	8 to 10	14	1
2. Thermal ion mass spectrometer	4 to 6	2	0.1
3. Solar wind and electron analyzer	7 to 10	15	0.4
4. Magnetometer	4 to 5	3.5	0.2
5. Imaging system	25 to 30	22	115
6. Collected dust analyzer	25 to 30	20	1
7. Dust counter	2 to 5	10	0.01
8. Radiometer	5 to 7	5	0.1
9. X-ray or γ-ray spectrometer	10 to 12	13	0.01
10. Optical spectrometer	5 to 10	4	2
Radar altimeter[a]			
Accelerometer[a]			
Total	95 to 125	108.5	115 (max)
Other Instruments			
a. Radio sounder	13	25	16
b. Plasma wave analyzer	1 to 3	2	0.05

[a]Part of engineering subsystem.

Table 1-4. Primary Measurement Objectives and Capabilities of Typical Instruments for Rendezvous

Reference to Table 1-3	Instrument	Primary Measurement Objectives	Desired Instrument Capabilities	Flight Instrument Development Status
1	Neutral mass spectrometer	Identification of parent molecules Atmospheric chemistry and neutral gas flow Isotopic composition of volatiles	Mass range: 1 to 250 amu Mass resolution: Δm = 1 amu for m = 1 to 140 amu $\Delta m \geq 1$ amu for $m \geq$ 140 amu Dynamic range: $\sim 10^6$ Sensitivity: $\geq 10^3$ cm^{-3}	Similar instruments exist; add dust protection
2	Thermal ion mass spectrometer	Ionic composition, temperature, and velocity Identification of ionization mechanisms near comet	Mass range: 1 to 100 amu Mass resolution: Δm = 1 amu Sensitivity: $n \geq 0.1$ cm^{-3} $T \geq 150$ K $E < 50$ eV	Similar instruments exist; add dust protection
3	Solar wind (positive ion) analyzer	Interaction of solar wind with comet (bow shock, contact surface, stability) Acceleration of ions near comet to form tail	Mass range: 1 to 45 amu Mass resolution: Δm = 1 amu Velocity range: 1 to 400 km/s Flux range: 10^4 to 10^9 $cm^{-2}s^{-1}$ ion^{-1}	Similar instruments exist; add dust protection if necessary
3	Electron analyzer	Ionization phenomena near comet Interaction of comet with solar wind	Energy range: thermal to several keV Sensitivity: 0.1 to 10^5 electrons/cm^3	Good instruments exist
4	Magnetometer	Magnetic properties of ionosphere and relation to ionization and ion acceleration mechanisms	Field range: 10^{-1} to $10^3\gamma$ Vector measurements Response to 10 Hz	Good instruments exist

Table 1-4. (Cont'd)

Reference to Table 1-3	Instrument	Primary Measurement Objectives	Desired Instrument Capabilities	Flight Instrument Development Status
5	Imaging system	Gross physical properties of nucleus (size, shape, rotation, optical properties) Physical and chemical heterogeneity of nucleus Evolution of surface Morphology of coma and tails of Halley Navigation and adaptive strategy	Sensor: CCD (800 x 800) UV enhanced Wavelength range: 1800 to 10,000 Å All reflective optics Spatial resolution/field of view: 1×10^{-5} rad/0.23 deg 5×10^{-5} rad/1.15 deg 2×10^{-4} rad/4.9 deg	Need dust protection; need new optical design
6	Collected dust analyzer (single package with several analyzing techniques)	Elemental abundance ratios for volatiles and nonvolatiles of bulk samples and individual particles Relation to meteorites	12 to 15 elements, including volatiles Sample amounts: 10^{-7} to 10^{-4} g/cm^2	Collector under study and development; good instruments exist for bulk analysis; laboratory instrumentation for individual particle analysis needs extensive adaptation
7	Dust counter	Dust flux and mass/size distribution Dust size, shape, velocity, electric charge	Size range: 0.3 to 300 μm Mass threshold: 10^{-13} g Velocity range: $1\text{-}10^{3}$ m/s	Laboratory instrumentation needs adaptation
8	Infrared radiometer	Temperature and energy balance of surface Thermal inertia of surface Dust envelope	Wavelength range: 10 to 60 μm Spectral resolving power: 10 Field of view: 10^{-3} rad	Instruments exist; need dust protection (?)
8	Millimeter-wave radiometer	Temperature and energy balance of surface Thermal and electrical properties of surface	Wavelength range: 1 to 10 mm Field of view: 10^{-2} rad	Relevant technology exists

Table 1-4. (Cont'd)

Reference to Table 1-3	Instrument	Primary Measurement Objectives	Desired Instrument Capabilities	Flight Instrument Development Status
9	Orbital X-ray fluorescence spectrometer	Elemental abundance ratios for certain nonvolatiles (Al, Si, Mg, Ca, Ti, Fe)	Energy range: 0.5 to 9 keV	Good instruments exist; sensor cooling problem
9	Orbital γ-ray spectrometer	Elemental abundances of H, C, O, Mg, Al, Si, Ca, K, Ti, Fe, Th, U in nuclear surface Relationship to meteorites	Energy range: 0.1 to 10 MeV High resolution detector Boom mounting	Similar instruments exist; cooling required
10	Infrared reflectance spectrometer	Chemical homogeneity of nucleus Identification of ices and mineralogy of some nonvolatiles	Wavelength range: 0.7 to 5 μm Spectral resolving power: $\sim$100 Field of view: $\sim$10 mrad	Instruments exist; need dust protection (?)
10	Ultraviolet spectrometer	Atmospheric and ionospheric composition and production rates Scale lengths of observable species Dust albedo and distribution around comet	Wavelength range: 1100 to 4000 Å Resolution: $\sim$10 Å	Good instruments exist; need dust protection
—	Radar altimeter	Mass, shape, and density of nucleus Supplements imaging objectives Navigation	Resolution: Velocity: <1 m/s Range: 25 m at 200 km	Technology exists
—	Accelerometer	Mass of nucleus Navigation	Range: 10^{-4} to 10^{-9} m/s^2 Accuracy: 0.1% of full scale	Technology available

Table 1-4. (Cont'd)

Reference to Table 1-3	Instrument	Primary Measurement Objectives	Desired Instrument Capabilities	Flight Instrument Development Status
a	Radio sounder	Internal structure of nucleus Existence and size of core Thickness of ice crust	Sounding depth: 1 km in ice 100 m in permafrost Range resolution: ≤ 15 m	Similar airborne instruments available; technology exists; space-qualified detector required
b	Plasma wave analyzer	Relation of plasma and field instabilities to ionization and ion acceleration mechanisms Interaction of comet with solar wind	Wave modes: electrostatic, hydromagnetic, and electromagnetic Frequency range: ~ 10 to 10^5 Hz Sensitivity: $\geq 10^{-1}$ γ $\geq 10^{-5}$ V/m	Good instruments exist
—	Landed science	Temperature of surface, Surface strength Experience and exploration	(1) Accelerometer (2) Thermal sensor (3) Imaging adapter (4) Etc.	(1) Good instruments exist (2) Good instruments exist (3) Needs study and development (4) ?

Table 1-5. Relation of Typical Rendezvous Payload to Science Objectives

Science Objectives	Instrument
(1) Determine the chemical nature and physical structure of comet nuclei. . .	Neutral mass spectrometer Imaging system X-ray or γ-ray spectrometer Optical spectrometer Radar altimeter and accelerometer Radiometer Collected dust analyzer Dust counter Magnetometer Radio sounder
. . . and characterize the changes that occur as functions of time and orbital position	Imaging system Optical spectrometer Neutral mass spectrometer Radiometer Collected dust analyzer Dust counter
(2) Characterize the chemical and physical nature of the atmospheres and ionospheres of comets as well as the processes that occur in them, and characterize the development of the atmospheres and ionospheres as functions of time and orbital position	Neutral mass spectrometer Thermal ion mass spectrometer Solar wind/electron analyzer Magnetometer Plasma wave analyzer Optical spectrometer Imaging system Dust counter Radiometer
(3) Determine the nature of comet tails and of the processes by which they are formed, and characterize the interaction of comets with the solar wind	Solar wind/electron analyzer Magnetometer Plasma wave analyzer Thermal ion mass spectrometer Imaging system Optical spectrometer Collected dust analyzer Dust counter

gases, the detection of reactive species, problems of mass overlap, and problems associated with operation in the expected dusty environment. The understanding of the chemical processes in the coma requires the observation of both neutral and ionized species. Measurement of the velocity distributions will add to our understanding of the physical processes occurrring in the coma. More detail is given in the report of the Mass Spectrometry Subgroup (see Part Two).

2. Plasma Observations

Several instruments in the rendezvous payload given in Table 1-3 (the thermal ion mass spectrometer, the solar wind and electron analyzer, the magnetometer, and the plasma wave analyzer) are needed to study plasma processes occurring within the coma and in the interaction of the comet with the solar wind. We believe two different types of ion detectors, called a thermal ion mass spectrometer and a solar wind analyzer in Table 1-3, are necessary to study the broad range of particle energies and directions of incidence. Both thermal and energetic electrons must be monitored to understand the interaction and ionization phenomena. A plasma wave analyzer is recommended in addition to a magnetometer and plasma spectrometers to study the exchange and dissipation of energy occurring in the interactions of the cometary plasma with the mass-loaded solar wind and the interplanetary magnetic field. In all of these areas, there is good instrumentation which would require only moderate or no modification for use on this mission. More details are given in the report of the Plasma Physics Subgroup (see Part Two).

3. Imaging System

The recommended imaging system consists of two cameras, with three fixed focal lengths, mounted on the scan platform. The need for three focal lengths is determined by the great range of linear scales and brightnesses of cometary phenomena and by the extreme range of observing distances which must be contended with during the mission. The recommended system concept has been developed around the properties of the 800 x 800 charge-coupled-device detectors presently being used in the Space Telescope wide field camera as well as the Galileo imaging system. We prefer the ultraviolet-enhanced version of this detector, which would allow high-quality imaging in the spectral range from 1800 to 10,000 Å. This broad spectral range requires that the system optics be all reflective. We also recommend the inclusion of about 15 to 20 filters. Although the optical properties of such an imaging system are radically different from the camera being used on Galileo, a great degree of commonality may exist in the area of electronics and filter mechanisms.

4. Dust and Solids Investigations

Achievement of the science objectives requires analysis of 12 to 15 elements, including the constituents of ices and organic compounds, in both bulk samples and individual particles. The collected

dust analyzer is envisaged as a package of two to four different analysis techniques which share, to varying degrees, a dust collection and distribution facility, a detector cryogenic cooling unit, and some electronics. The dust counter listed in Table 1-3 is envisaged as an instrument which monitors the flux of dust particles. Besides its scientific value, the data from this instrument would be used to design the adaptive mission strategy required to explore Tempel 2.

5. Remote Sensing

The radiometer could operate in either the infrared or millimeter-wave spectral regime. Either instrument would be mounted on an articulating platform. Infrared radiometers have flown on numerous missions (Mariners 9 and 10, Viking); millimeter-wave radiometers are now under development.

Either x-ray or γ-ray techniques, or a combination of both, should be considered for remote-sensing compositional studies of the nucleus of Tempel 2. Both types of instrumentation have been flown in the Apollo missions.

The optical spectrometer in Table 1-3 is a remote sensing instrument, to be mounted on the scan platform, intended for study of the coma and/or the nucleus. Useful wavelength ranges span the ultraviolet, visible, and infrared. It is understood that probably a single instrument cannot accomplish all of the optical spectrometer goals discussed in the reports of the Subgroups on Remote Sensing of the Atmosphere and of the Nucleus, and that the selection of flight instrumentation for this mission will be difficult. Specific options among already existing instruments include the ultraviolet spectrometers on Voyager, Pioneer Venus, or Galileo; the near-infrared mapping spectrometer on Galileo; and the pressure-modulated radiometer on Pioneer Venus.

6. Mass Determination, Radar, and Radio Sounding

The important scientific objectives of determining the mass, density, gravity field, and surface properties of Tempel 2 depend primarily on instruments that are part of the engineering subsystem: accelerometer, radar altimeter, and communication radio. Specifications necessary to achieve the scientific objectives therefore must be combined with engineering requirements and will require close coordination between scientists and engineers in both the instrument development and operations phases of the mission. Optimal use of on-board instrumentation and ground-based tracking requires continuation of theoretical studies of this problem currently in progress.

Radio sounding probably represents the only feasible method of investigating the deep internal structure of a comet nucleus on the first mission. Although similar instruments are used to sound glaciers on Earth, no flight-tested prototype instrument of this kind exists. Continued study and development of an appropriate instrument are necessary if this objective is to be achieved.

D. TYPICAL PAYLOAD AND MEASUREMENT OBJECTIVES: HALLEY COMA PROBE

The science rationale for a coma probe at Halley and the optimum payload were worked out by a Subgroup whose full report appears in Part Two of this document.

For safety considerations discussed in Section V, the main spacecraft will not be targeted closer to Halley than 130,000 km on the sunward side — a distance too great to permit optimal direct sensing of the coma.

A very large advance in scientific return from the Halley flyby can be achieved by sending a short-lived, expendable probe directly into the coma. Such a probe is necessary to:

(1) Detect and measure atmospheric species which do not have convenient spectral lines for remote sensing.

(2) Obtain unambiguous measurements of the flux, size distribution, and composition of emitted dust.

(3) Study the main features of the comet-solar wind interaction.

(4) Study the gross characteristics of the Halley nucleus.

The main scientific objectives of the probe measurements should be the study of the:

(1) Composition, flux, and size distribution of dust.

(2) Composition and flux of parent molecules.

(3) Physics and chemistry of the coma.

(4) Physical or plasma mechanisms involved in the comet-solar wind interaction.

A representative probe payload which will address these objectives is shown in Table 1-6.

E. QUESTION OF A TAIL PROBE AT HALLEY

In its report the CHSWG considered the deployment of a probe into the tail of Halley during the proposed rendezvous with that comet. The rationale was that only *in situ* measurements within the tail of an active comet could address some of the key issues implicit in Objective (3).

As a rendezvous with Halley is no longer possible and the present mission involves only a flyby of this comet, the CSWG has chosen to extend the probe capability to study the near nucleus region of Halley

Table 1-6. Representative Probe Payload

Instrument	Mass, kg	Power, W	Maximum Data Rate, kb/s
Dust analyzer	8	10	3
Dust counter	1	1.5	0.1
Neutral mass spectrometer	7	8	2
Ion mass spectrometer	7.5	5	1.6
Electron and proton analyzer	5	5	1
Magnetometer	3.5	3.5	1
Plasma wave analyzer	3	3	1
Imaging system	5	7	2.5
Total	40	43	12.2

for what we consider to be powerful scientific reasons (Section IV-D; and Section IX of Part Two). Nevertheless, having made this necessary choice (the mission cannot accommodate both a coma probe and a tail probe at Halley), we will fly by this very active comet without having made any detailed study of its tail. This omission cannot be fully remedied at Tempel 2, since this comet has at most a very modest tail; it is also difficult to fit any extended tail excursion into the mission strategy at Tempel 2 (Section V) without compromising the nucleus-intensive science on the rendezvous spacecraft.

The CSWG feels that the scientific value of the Halley Flyby/ Tempel 2 Rendezvous mission described in this document would be greatly enhanced if an independently launched probe were to encounter the tail of Halley at the time that the coma probe and the rendezvous spacecraft are in the comet's vicinity. A suitable encounter distance might be about 10^5 to 10^6 km from the nucleus.

Except for dust analyzers, the instruments on such a tail probe should be similar to those on the Geomagnetic Tail Laboratory (GTL) part of the planned OPEN Mission (see Origin of Plasmas in the Earth's Neighborhood: A Mission Synopsis, National Aeronautics and Space Administration, February 1979). The recommended GTL payload includes instruments to measure magnetic fields, DC electric fields, plasma waves, solar wind plasma, three-dimensional hot plasma (both energy and mass spectra), energetic ions, and energetic electrons. A minimum payload for such a tail probe would include the instruments listed in Table 1-7.

Table 1-7. Independently Launched Tail Probe: Minimum Payload

Instrument	Mass, kg	Power, W	Bit Rate, kb/s
Magnetometer	3	6	1
Plasma wave detector	4	3	1
Solar wind, heavy ion, and electron analyzer(s)	9	4	2
Dust impact counter and analyzer	5	10	1
Total	21	23	5

We recommend that NASA pursue any possibilities of international cooperation in implementing such an independently launched Halley tail probe.

SECTION V

MISSION STRATEGY

A. INTRODUCTION

Although the rendezvous with Tempel 2 is the primary objective of the Halley/Tempel 2 mission, the encounter with Halley is of extreme scientific importance. It is essential to design a mission strategy that maximizes the amount of complementary data concerning the physical and chemical properties of these two very different comets.

B. HALLEY FLYBY WITH A PROBE

If a single spacecraft is to fly by Halley on its way to a rendezvous with Tempel 2, the flyby can occur only when Halley is about 1.5 AU from the sun, before perihelion. Figure 1-3 shows the spacecraft trajectory for this opportunity to study two comets with a single launch.

The detailed strategy for the Halley encounter evolved by the CSWG was based on the following four considerations:

(1) To accomplish the rendezvous with Tempel 2, the main spacecraft must survive the Halley flyby in good condition.

(2) The scientific returns from both the main spacecraft and the probe are inversely related to the distances of closest approach; the closer the better.

(3) For good imaging, the main spacecraft should pass on the sunward side of Halley. While approaching and receding from comet Halley, the main spacecraft's imaging system will view the comet's tail; near closest approach, it will study the region of the comet's nucleus.

(4) The navigation system can deliver the probe to any desired region within the Halley atmosphere with an estimated cross-track accuracy of about ±2200 km (3σ).

Dust is the most serious environmental hazard in the vicinity of Halley. At the relative velocity of 50 to 60 km/s, characteristic of Halley flyby, dust can be extremely hazardous to some spacecraft components and to some science instruments. Thus, it is necessary to keep the trajectory of the rendezvous spacecraft in essentially dust-free regions. Newburn and Sekanina have constructed models of the density of dust particles expected near Halley at the time of the flyby. These models indicate that, on the sunward side of the nucleus, dust particles are decelerated and then turned around and accelerated away from the sun by solar radiation pressure. A steady-state model predicts that the dust

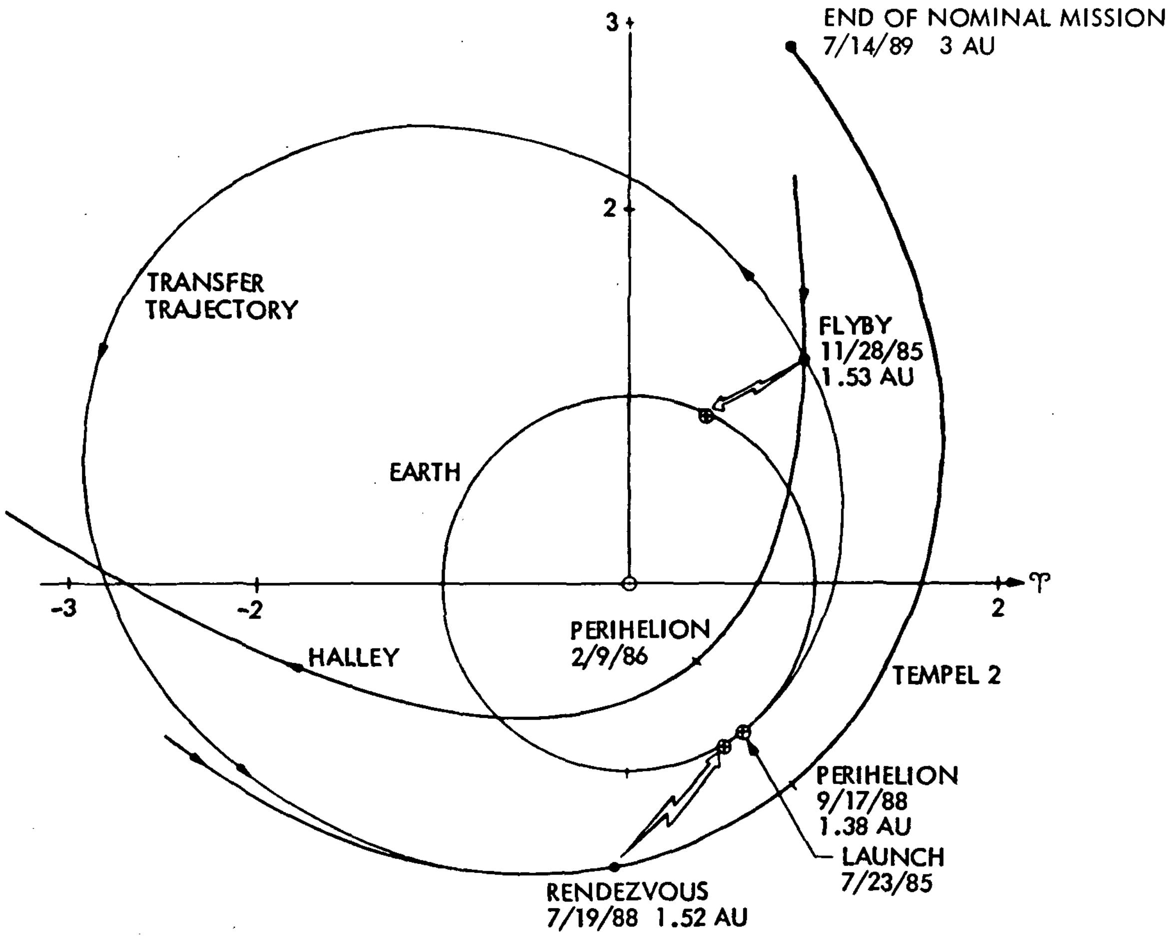

Figure 1-3. Heliocentric Trajectory (Ecliptic Plane Projection)

will be confined within a parabola centered on the nucleus with its apex (4.3 ±2.4) x 10^4 km sunward of the comet. Becuase of the uncertainty of the model and the unpredictability of local outbursts of dust emission, a conservative choice of the apex distance of the parabolic dust envelope is about 10^5 km. The geometry of the encounter is such that an apex distance of 1.0 x 10^5 km corresponds to a closest approach distance of 1.3 x 10^5 km for a sunward pass.

In view of the dust hazard, the CSWG recommends that the rendezvous spacecraft be targeted to pass approximately 10^5 km sunward of Halley. Such a trajectory will yield good remote sensing of the inner coma and resolve the nucleus without exposing the rendezvous spacecraft to unnecessary danger from dust. We note that the models indicate that, on the anti-sunward side, the plasma tail and the dust tail separate at about 10^7 km from the nucleus. Thus, it is not possible to target the rendezvous spacecraft to pass through the ion tail while avoiding the dust and still fulfill the major objectives of the Halley flyby. First, the deflection of the main spacecraft 10^7 km away from the sun after the release of the probe requires that the probe be released such a long time before encounter that it could not be delivered sufficiently close to the nucleus; that is, the probe delivery error would be unacceptably large. Second, the remote sensing of Halley's inner coma and nucleus would be seriously compromised by the large miss distance and nonoptimal lighting conditions.

Whereas the rendezvous spacecraft must avoid the dust at Halley, the probe must interact with it to study its properties. The science objectives require that the probe get as close to the nucleus as possible where the dust and gas densities are the highest. The CSWG recommends that the probe be targeted directly at the nucleus and that adequate protective dust shieldings be included to ensure that the probe survives the near-nucleus environment of Halley. There are important scientific reasons for decreasing the estimated 3σ miss distance from its present value of ±2200 km to go as close as possible to the nucleus. The chances of actually hitting the nucleus, if the probe is aimed directly at it, are negligible.

C. TEMPEL 2 RENDEZVOUS

The mission strategy at Tempel 2 should meet all of the major science objectives of the rendezvous mission while minimizing the environmental hazards to the spacecraft for as long as possible into the mission. The mission outlined below is divided into four main phases and lasts 1 year after rendezvous. The strategy reflects our desire to get as close to the nucleus as possible for as long as possible, tempered by our awareness of the dust hazard in this little-known environment.

The comet's activity and the associated dust hazard will vary with time. Although we know that this activity will be greatest shortly after perihelion, the details of the variation are poorly understood and

essentially unpredictable. Hence, the overall mission strategy must be cautious and adaptive. The strategy must also recognize that a few key instruments must get very close to the nucleus ($\sim$10 km) before they can obtain their prime data. Finally, the time variability of cometary phenomena must be folded into the observing plan as must the vast range of scale of phenomena which are of interest, going from 10^{-1}-meter inhomogenieties on the surface of the nucleus to 10^{5}-km structures in the coma.

The specific rendezvous strategy outlined below results from the following considerations:

(1) The spacecraft should arrive at Tempel 2 as long as possible <u>before</u> perihelion to maximize the duration of pre-perihelion observations. The arrival time depends on the ion drive performance and the spacecraft mass. It is highly desirable that the spacecraft arrive before the comet is at 1.5 AU from the sun on its inbound trajectory.

(2) The strategy should take advantage of our knowledge of the comet's past behavior. The comet's activity is expected to rise steeply to a maximum some 20 days after perihelion and then to decrease more gradually with time (Figure 1-4). To take advantage of the comet's relatively quiescent nature before the peak of activity, we suggest an initial close pass by the nucleus at an approximate range of 100 km (Phase 1). As the cometary activity and the resulting dust hazard increase near perihelion, the spacecraft should back away to a safe distance (Phase 2) and, if feasible, make an excursion into the tail region. Then the spacecraft should again make close approaches to the nucleus as the activity subsides (Phase 3). As the comet settles into its post-perihelion quiescent state, the spacecraft should attempt to orbit the nucleus at a range of about 10 km (Phase 4). The rendezvous mission should be terminated by an experimental descent onto the comet's nucleus.

(3) There is a conflict between the scientific desire to analyze cometary dust and the concern for the spacecraft's safety in a dusty environment. Several possible strategies could be used to minimize this conflict:

(a) The dust-collection efficiency can be maximized by using a sticky collector surface and by exposing several collection surfaces simultaneously.

(b) Several trajectory legs or periods should be devoted to dust collection. During these periods, sensitive instruments and spacecraft subsystems could either be covered up or stowed in relatively safe configurations. For example, solar panels could be feathered so that the dust flow is nearly parallel to the plane of the array or could be turned with their backs to the nucleus.

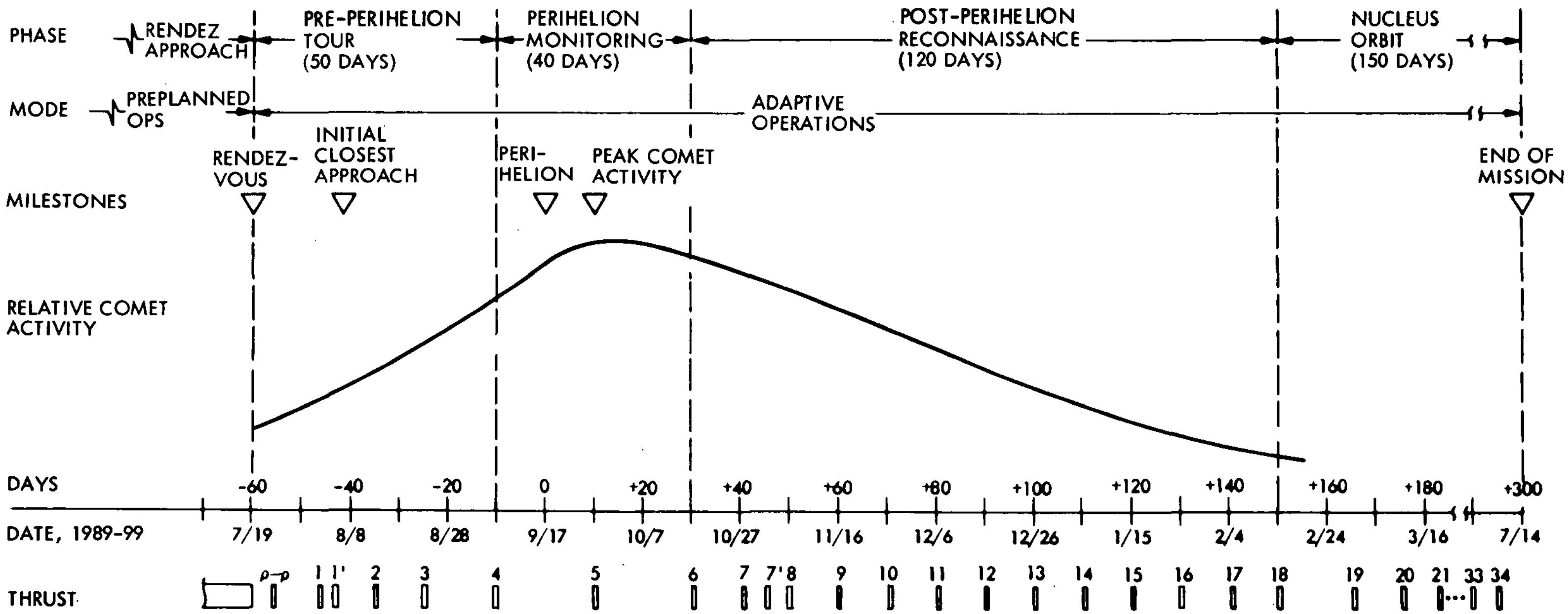

Figure 1-4. Tempel 2 Profile Strategy Timeline

(c) Some degradation of instruments or spacecraft subsystems should be accepted, especially toward the end of the mission. For example, the mission could still be carried out if, after achievement of the Tempel 2 rendezvous, the efficiency of the solar panels was degraded to 50 percent by dust.

(d) The optimization of the dust-collection sequences requires an adaptive strategy. The spacecraft must be able to monitor the dust environment in real time and initiate a retreat maneuver should the environment become too hostile.

(4) Although the spacecraft can be rotated easily around the axis of the solar arrays, the rotation of the spacecraft about an axis normal to the solar arrays requires thrusting and is quite slow (∿0.2 deg/min). Thus, to facilitate the pointing of bus-mounted instruments, comet-centered orbit planes of the spacecraft should include the sun-comet line during rendezvous trajectories.

The following rendezvous mission scenario assumes the payload identified in Section IV. The imaging system, the solar wind and electron analyzer, magnetometer, dust counter, and optical spectrometers can gather data nearly continuously once the rendezvous is achieved. For the remaining instruments, possible operating times are more strictly governed by the spacecraft-comet range (see Figure 1-5). During all four rendezvous phases, if a particular instrument is within range, it is assumed to be operating unless otherwise stated. The boundaries of the mission phases are not rigid. For example, if during the perihelion monitoring phase (Phase 2, below) the cometary environment appears safe for the spacecraft, the post-perihelion reconnaissance (Phase 3, below) could be initiated early.

1. Phase 1: Rendezvous and Quick-Look Approach (Rendezvous to P - 10^d)

The Tempel 2 rendezvous occurs at perihelion (P) minus 60 days (P - 60^d) at a heliocentric distance of 1.53 AU, a phase angle of 90 deg, and a spacecraft-comet range of 5000 km. An initial sunward flyby of the nucleus is made at a minimum range of about 100 km. The spacecraft then backs away to a safe distance (∿4000 km) in the sunward hemisphere while monitoring the rapidly increasing cometary activity. During this phase, an approximate determination is made of the mass of the nucleus. The imaging and dust experiments assess the hostility of the near-nucleus region. All scientific instruments operate over periods determined by the spacecraft-comet range (Figure 1-5).

2. Phase 2: Perihelion Monitoring (P - 10^d to P + 30^d)

During this phase, the comet reaches perihelion at a heliocentric distance of 1.38 AU and is expected to reach peak activity near

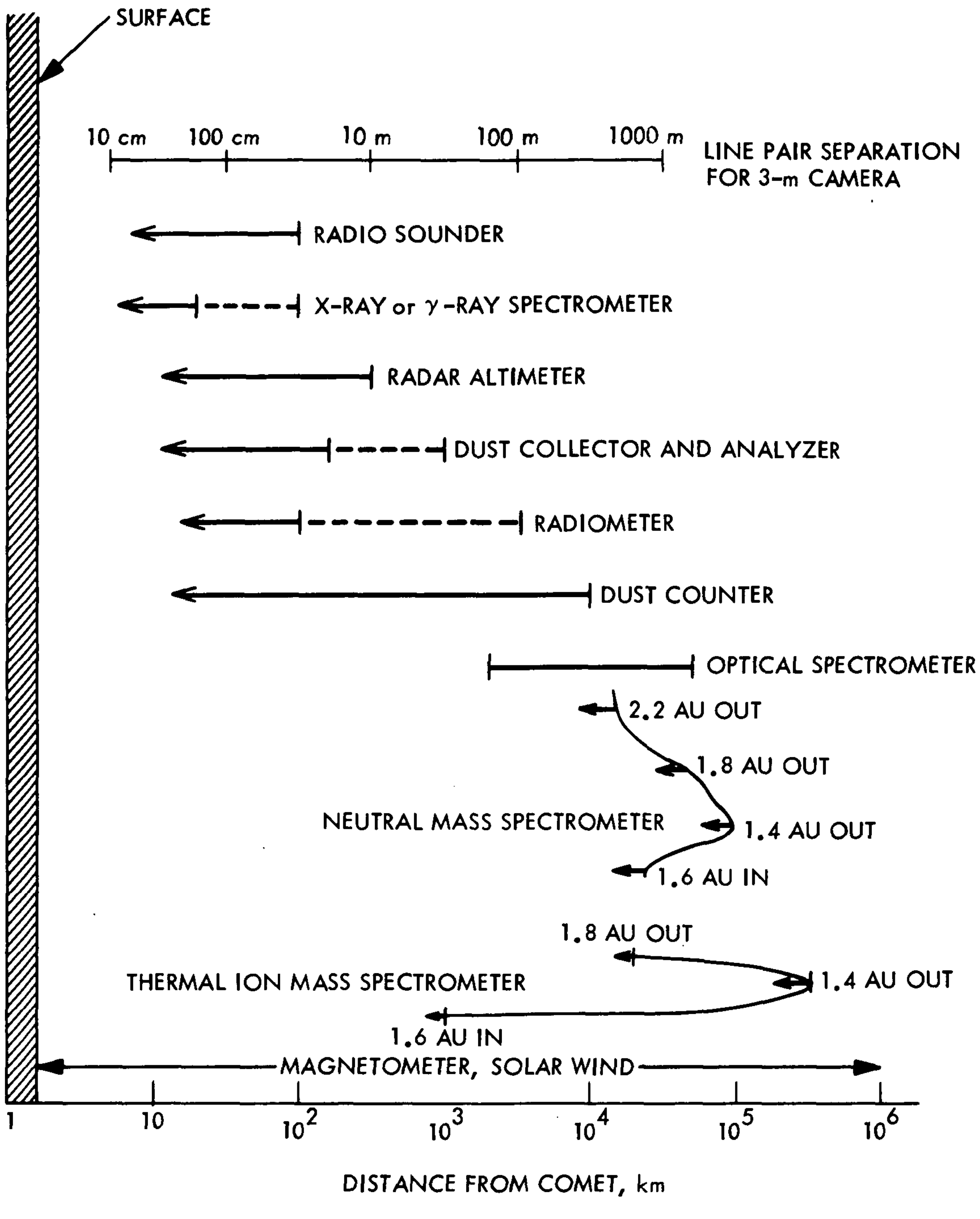

Figure 1-5. Operation Ranges of Instruments at Tempel 2 Rendezvous. Where both a solid and dashed line are shown, the solid line indicates the distance of prime data gathering. The distances to which the neutral and ion mass spectrometers can gather data are functions of orbital position.

P + 20^d. The spacecraft will monitor the comet from a safe distance (∿4000 km). Most of this time would be spent in the sunward hemisphere to allow observing of the comet at phase angles ranging from 40 to 80 deg. During this phase it might also be possible to make an excursion in the anti-sunward direction to study tail phenomena. As a propellant expenditure of about 8 kg and a round-trip time of about 3 weeks is considered reasonable for such a trip, it can be seen with the aid of Figure 1-6 that the extent of such an excursion would be about 30,000 km downstream of the nucleus. At the end of Phase 2, the spacecraft should be in a location suitable for initiating the first nucleus pass of the next phase.

3. Phase 3: Post-Perihelion Reconnaissance (P + 30^d to P + 150^d)

The cometary activity fades gradually as the comet's heliocentric distance increases from 1.4 to 2 AU. During this 120-day period, several passes of the nucleus are made to collect dust. Instruments susceptible to dust contamination (such as neutral mass spectrometers, imaging system, infrared spectrometer) may have to be shielded during part of this period. Beginning at a range of approximately 10^3 km, dust collection passes will be made at successively closer ranges, if the dust hazard does not become too severe. An assessment of the science data and spacecraft health will be made before committing to a closer pass. The large and continuous changes in phase angle (0 to 90 deg), the proximity of the spacecraft and comet (<500 km), the long residence time (120 days), and the cometary activity combine to make this phase an optimum period for detailed atmospheric and dust studies.

4. Phase 4: Nucleus Orbiter (P + 150^d to P + 300^d)

As the comet's heliocentric distance increases from 2 to 3 AU, the cometary activity is expected to be very low. The dust hazard will diminish, making it possible to emphasize nucleus-intensive studies. The spacecraft will be inserted into a near-circular orbit of 50 km or less. If possible, the spacecraft will spend at least 4 weeks in a close (∿10 km) orbit of the nucleus to obtain an accurate mass determination. A radio sounder, a radiometer, and the remote sensing x-ray or γ-ray spectrometer would obtain their best data during this phase of the mission because this is the only time they can resolve the nucleus. The imaging experiment would achieve a resolution of 10 cm with a 3-m focal length camera. During this phase of the mission, the radar altimeter and imaging system would be used in an attempt to select a region of the nucleus suitable for a later experimental descent onto the surface.

The spacecraft will gradually descend to lower and lower orbits and finally attempt contact with the comet. Without imposing any costly constraints on the spacecraft design or mission operations, this operation should be carried out in such a way as to provide the best chance for

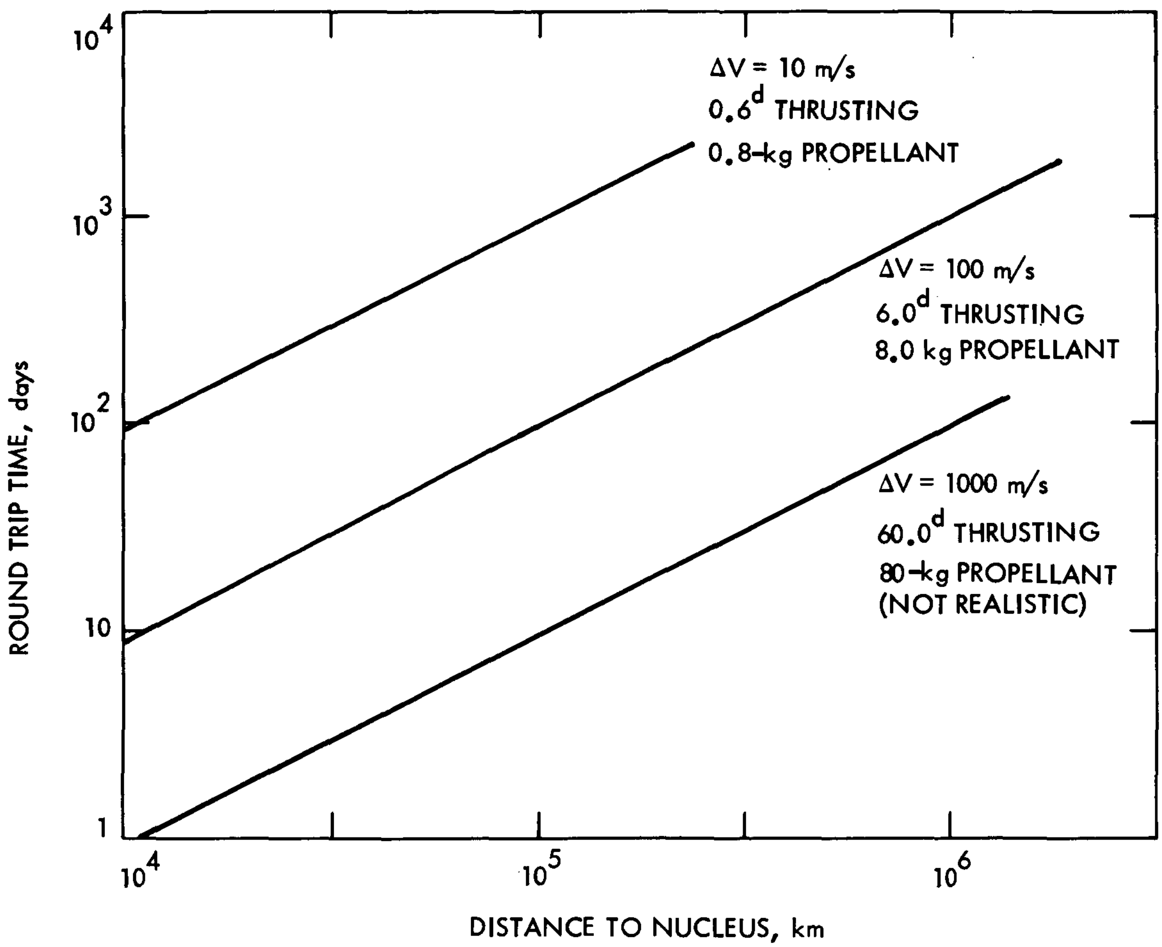

Figure 1-6. Approximate Velocity Increment and Trip Time Required for a Tail Excursion During the Tempel 2 Rendezvous. Round-trip time assumes impulsive ΔV application.

survival of the instruments and for continuing communication between the Earth and spacecraft after contact with the surface. The primary objective of this maneuver is to provide knowledge of the mechanical properties of the comet's surface and of the hazards associated with a future landing. This maneuver will provide knowledge invaluable for future sample return missions, and provide physical data unobtainable in any other way. The descent should occur while the comet is observable from Earth-based observatories.

SECTION VI

FOLLOW-ON MISSIONS

A. INTRODUCTION

Because of the complexity of cometary phenomena and the diversity among comets, a single mission to one or two comets will not yield all the information needed to understand comets and their relationship to the rest of the universe. The Halley/Tempel 2 mission is an outstanding first mission because it will provide fundamental data on two very different kinds of comets. But, even after this mission, and no doubt in part as a result of it, important questions will remain unanswered. The CSWG believes that a sample return mission is an essential step toward answering many fundamental questions concerning comets.

B. SCIENCE RATIONALE FOR SAMPLE RETURN

A sample of a comet is likely to be the most primitive extraterrestrial material that we can ever hope to study. From the atmospheres that comets form as they approach the sun, we know that comets formed, and many haved remained, at low temperatures. From their small size, we infer that comets have not been modified by internal processes. Not only may information regarding the condensation and agglomeration of the primitive solar system be held "frozen" within comets, but the odds are high that some of the cometary dust grains are pristine interstellar material. No other class of solar system object is likely to have preserved so clearly the record of the processes by which primitive materials formed.

Of the science objectives identified in Section III, some measurements relating to the nature and origin of the nucleus can be carried out only on returned samples. Several of these experiments or measurements are listed in Table 1-8. But even this impressive list does not include all the subtle problems which could be addressed by laboratory analysis. For example, current evidence indicates that primitive interstellar dust originated in several distinct settings (supernovae, novae, red giants, planetary nebulae, protostellar nebulae, and interstellar space). If we could study individual grains in detail, we might discriminate among materials formed in different locations. We would learn about both astrophysical processes and formation processes in the solar system. Comets offer a unique opportunity to sample "star dust" and the raw materials of the solar system.

A single sample returned from the nucleus of a comet would give more complete information about the formation of comets than would the first sample from a planet whose heterogeneous surface and stratified interior preclude obtaining representative materials by sampling at a single location. As comets are presumed to have had simple evolutionary histories, the probability of obtaining a representative sample at a single landing site is very high.

Table 1-8. Measurements Best Made on a Sample From a Comet

Measurement	Applies to
Ices	
Density, structure, morphology, composition	Thermal history, formation conditions
Isotopic compositions of H, C, N, O and noble gases	Relation to planetary atmospheres, sun, nucleosynthesis
Organic chemistry (minor and trace components)	Pre-biotic chemistry, interstellar molecules, condensation
Thermal conductivity	Thermal history
Electrical conductivity	Solar wind interaction, thermal emission
Dust and Rocks	
Age determination	Origin of comets, solar system
Isotopic compositions	Nucleosynthesis, interstellar matter, cosmic rays
Trace element composition	Condensation, nucleosynthesis
Petrography and petrology	Accretion, origin, evolution of cometary material
Mineralogy	Condensation, thermal history
Radioactivity	Cosmic ray, stellar/solar wind interactions
Magnetic, thermal, electrical properties	Interaction with solar fields, thermal history
Density	Origin, structure of cometary material, relation to meteors
Radiation damage	Cosmic rays, stellar/solar wind interactions

An important point, discussed on the next page, is which comet one should sample. There are many comets; available evidence indicates that there are large variations in their observed, and presumably also in their unobserved, properties. Although it is desirable to eventually sample as much of this range as possible, it is equally clear that the study of material from just one comet will produce a major increment in our knowledge of fundamental processes in the early solar system and perhaps even in the interstellar medium.

Although sample return from a comet is an essential part of cometary and solar system exploration, it is not an ideal first mission. Too little is known about the cometary environment to allow an adequate mission at reasonable cost. Especially neeeded is information about cometary activity, the dust environment, and the physical properties of the nucleus. It is also desirable to know how heterogeneous the surface of a nucleus is. Data from a precursor rendezvous mission will permit a sample return mission that is more cost-effective and better planned scientifically. Direct sampling is required to obtain the highly precise data regarding the physical and chemical properties of the icy and nonvolatile constituents of comets which are needed to unravel the origins and the interrelationships of these materials.

C. PRACTICAL CONSIDERATIONS

1. Which Comet?

It is unlikely that we will know enough about comets before the successful completion of the first comet mission to make any intelligent choice of a candidate comet for a sample return. Data obtained during the first comet mission should increase our knowledge of the near-nucleus environment and increase our confidence in being able to effect a successful sample return. Data obtained during the first mission will make it possible to assess hazards realistically and to determine key engineering parameters such as the bearing strength of the nucleus, the availability of smooth landing sites, the likely ease or difficulty of collecting samples, etc.

It is likely that we will also learn more about comets in general and be able to understand better the meaning of the different types of behavior that have been observed from Earth. At that point we should be able to decide more rationally which type of comet should be sampled first.

Inevitably the comet studied during the first rendezvous mission will be a prime candidate for the first sample return. Study of the rendezvous spacecraft left behind after the first mission would yield important scientific and engineering data.

2. Active Versus Passive Sampling

Direct sampling of the nucleus is the least biased method of collecting cometary material. It is probably the only way in which the pristine volatile fraction can be studied. It is not clear whether the remote collection of dust can provide an unbiased sample of the nonvolatile constituents of the nucleus.

3. Types of Samples

In order to study undisturbed ices, subsurface samples must be obtained by coring and trenching. These methods have been employed successfully on the surfaces of rocky planets (moon and Mars). In addition to subsurface samples, scoop and rake samples of surface materials would be desirable.

Investigators who have participated in the Apollo and Luna sample studies feel very strongly that "more is better." In a trade-off between quantity of sample and almost anything else such as documentation, sampling methods, target comet, and to some degree even preservation conditions, quantity is deemed more important. It is clearly important to plan the sampling protocol to maximize the variety of material returned to the Earth, but generally it is far better to plan to have the luxury of being selective on Earth rather than at the target.

4. Sample Transportation

Once obtained, the sample should be sealed in a container and maintained in an environment as close as possible to its cometary one, which is estimated to be a space vacuum with $T < 100$ K. However, it is probable that some important studies can be made on samples subjected to higher temperatures and pressures than these.

5. Terrestrial Handling

The pristine nature of the samples should be maintained to the greatest degree possible. Sterilization either by heat or radiation would alter many of the organic compounds and should be avoided.

6. Research and Development

It is essential that remote sampling technology at NASA be developed for the next generation of planetary exploration — including the sample return mission of the cometary program. Such technology has already been employed successfully in the Soviet lunar program.

PART TWO

REPORTS OF INSTRUMENT SUBGROUPS

SECTION I

INTRODUCTION

The first mission to a comet will pose new challenges in terms of instrument design. Although some science objectives can be achieved by using slight modifications of instruments flown on previous space missions, others will require extending the operating range of existing instruments to new limits, or even the development of entirely new instruments and investigative techniques.

The CSWG established seven subgroups to study in detail fundamental questions of experiment design and procedure which must be resolved to achieve the major science objectives established for a first comet mission. These seven subgroups were:

(1) Plasma Physics.

(2) Mass Spectrometry.

(3) Imaging.

(4) Remote Sensing of the Atmosphere.

(5) Dust and Solids Investigations.

(6) Remote Sensing of the Nucleus.

(7) Mass Determination, Radar, and Radio Science.

This part of this document consists of the reports of these subgroups (Sections II through VIII).

In addition, a special subgroup (the Halley Probe Subgroup) was established to consider the objectives, possible instrumentation, and strategy for a coma probe to be deployed from the main spacecraft during the flyby of Halley. The report of this subgroup is given in Section IX.

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SECTION II

REPORT OF THE SUBGROUP ON PLASMA PHYSICS

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J. Brandt
U. Keller
A. Nagy
M. Neugebauer
L. Burlaga (Advisor)

A. INTRODUCTION

A major scientific goal of a comet program is to determine the processes responsible for the production and maintenance of the gas, dust, and plasma envelopes of active comets. One fundamental problem in this area of comet physics is that of identifying the dominant mechanism that produces the ionization. Photoionization seems to be an inadequate source, and no generally accepted quantitative model now exists. Ionization produced by charge exchange with solar wind plasma or by fast electrons accelerated in the interaction of the solar wind with the magnetized cometary plasma is possible. Energy transfer by absorption of plasma waves (recently found to be operative at Venus) can also be significant. It seems certain that these basic dynamical questions about comets will remain open until detailed *in situ* plasma physics measurements are available from more than one type of comet and from more than one heliocentric location.

Many fundamental large-scale aspects of cometary structure and dynamics are also known to involve plasma processes, but in a number of important areas the basic mechanisms that are operative are poorly understood. The areas involving comets and plasma physics for which new *in situ* information is needed include:

(1) The comet as an obstacle in the solar wind (mass loading, the characteristics of the contact surface).

(2) The nature of the plasma flow (possible radial outflow or a cometary wind).

(3) Collisionless shocks (the bow shock, possible internal shocks).

(4) Plasma processes in the comet tail (disconnection events and substorms).

B. OBJECTIVES

The major science objectives of the plasma investigation are:

(1) To determine the processes that produce and control the distributions of ionized species in the coma and to analyze the local interactions of the cometary plasma with captured magnetic fields, current systems, plasma turbulence, and shocked solar wind.

(2) To determine the large-scale interaction between the solar wind and the coma and the range of variation with changing comet activity.

(3) To identify the transient plasma phenomena important in the coma and tail and to determine the mechanisms that control these transient phenomena. These phenomena include sudden enhancements of ionization (streamers), tail disconnection, possible discharges, substorm analogs, etc.

C. MEASUREMENTS NEEDED AND INSTRUMENTATION

To address the above scientific objectives, the following measurements are required.

1. Ion Composition

Measurements of ion composition profiles are required to study the ionization processes and to infer the composition of the cometary nucleus from which the ions must originate. It is desirable to measure ion abundances in regions where the partial density is as low as 0.1 cm^{-3} and as high as 10^5 cm^{-3}, and to determine the velocity distributions as well. Thermal ion mass spectrometers and instruments developed for solar wind and magnetospheric measurements could be utilized in the cometary plasma regime. Ion mass spectrometers capable of measuring characteristics of thermal ion distributions ($E \leq 10$ eV) and instruments designed to analyze more energetic ion populations (10 eV $< E <$ 20 keV) are well developed. Composition measurements are discussed in more detail in the report of the Mass Spectroscopy Subgroup. The mass analysis should be performed in such a way that a prior knowledge of the velocity distribution is <u>not</u> assumed.

2. Electron Distributions

Electrostatic plasma analyzers naturally provide important information on suprathermal electrons (E up to 50 keV, or so); but

since thermal electrons ($E < 10$ eV) are not generally studied suitably by such a system, it would be desirable to supplement the payload with a simple and well-developed ionospheric probe.

3. Solar Wind Plasma

The plasma probe to be flown on a comet mission should have high sensitivity for low-velocity ion flows with relatively high temperatures (10^7 K), so that good plasma measurements can be made all the way in to a contact surface. Solar wind measurements are required to complement the measurements made by the ion mass spectrometer in regions of high density. Such instruments may need some development for use on a stabilized spacecraft, and the cometary environment (dust and neutrals) may limit the achievable sensitivity. It is quite possible that a version of the ion composition spectrometer can incorporate adequate solar-wind measurements.

4. Magnetic Field

The magnetometer should be a triaxial vector instrument with good frequency (f) response ($f \leq 10$ Hz). The range of the instrument is dictated by the weakest interplanetary field expected at several AU from the sun ($< 1\gamma$) and the theoretically expected maximum field of the nucleus or trapped field region ($> 10^2\gamma$). Thus, a range 0.1 to $10^3\gamma$ is indicated. Instruments such as those described above have been flown successfully on previous missions. The magnetometer sensor should be boom-mounted.

5. Plasma Waves

At Halley and Tempel 2, plasma wave detectors should provide information for studies of wave-particle phenomena in the upstream solar wind, the bow shock region, near the contact surface, and within the cometary ionosphere. The upper frequency bound should be selected to cover all modes up to the electron plasma frequency, $f = 9\sqrt{N}$ kHz, where N is the density in electrons/cm^3. For penetration into the dense cometary ionospheres, where N(max) could be as high as 10^5 cm^{-3}, f should go up to 3 MHz, while if N(max) = 10^3 cm^{-3}, the upper frequency to be sampled need only be near 300 kHz. Simple plasma wave instruments could use only electric field sensors, and well developed instruments covering the necessary frequency range are readily available. For the Halley probe, the analyzer must have a rapid sample capability (several spectral scans per second) for use in the final few hours. The full instrument should also have a low-bit-rate analyzer with high-frequency resolution. This should be available for use in the distant upstream region, in the outer coma, and in the inner region near the contact surface. The rendezvous spacecraft might incorporate only a low-bit-rate analyzer with high-frequency resolution.

D. MISSION STRATEGY AND OTHER CONSIDERATIONS

1. Cruise

The plasma physics instruments on the rendezvous spacecraft should be operated in cruise to study the interaction of the ion drive thrusters with the solar wind plasma.

2. Low-Bit-Rate Mode for the Halley Probe

To study the possible large-scale interaction of Halley with the solar wind (i.e., mass loading; upstream plasma wave turbulence; upstream propagation of locally accelerated electrons and protons, etc.), the basic Halley instruments should be designed to operate in a mode with very low power and very low bit rate.

3. Tail Excursion at Tempel 2

If the tail of Halley is not directly explored, it is important that the Tempel 2 rendezvous spacecraft pass through part of the tail region of Tempel 2.

SECTION III

REPORT OF THE MASS SPECTROMETRY SUBGROUP

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A. INTRODUCTION

This report discusses the mass spectrometry of both neutral and ionized components of cometary atmospheres. The conditions during the fast flyby of Halley are very different from those obtained during the Tempel 2 rendezvous as far as the operation of the neutral mass spectrometers is concerned; for this instrument, these two components of the mission are dealt with separately.

B. OBJECTIVES

Composition measurements of the neutral and ionized components of the cometary atmospheres are necessary to accomplish three of the previously stated major objectives of this comet mission; these are to characterize the:

(1) Chemical, elemental and isotopic composition of the volatile components of the cometary material.

(2) Physics and chemistry of the cometary atmospheres and ionospheres.

(3) Interaction with the solar wind.

In order to achieve the first two objectives, it is of utmost importance to determine the chemical composition of the parent molecules (possibly H_2O, CO, CO_2, and more complex molecules) and the rates of their ejection from the nucleus. The measurement of the isotopic abundances of H, C, N, O and the noble gases is also important as it will yield important clues to the origin of comets. The primary instrument for making these measurements is the neutral mass spectrometer.

A chain of chemical reactions is probably initiated by ionization of one or more of the parent molecules in the coma. Subsequently, out to the limits of the collision region (about 10^2 km for Tempel 2 and 10^3 to 10^4 km for Halley), the chemical evolution of the cometary gases is probably dominated by ion-molecule reactions. Measurements of the relative abundances and energies of the neutral molecules and ions, by the neutral and ion mass spectrometers, will elucidate the processes controlling the chemistry in this region, which in turn will yield information on the composition of the parent gas. Information on the velocity distribution is important for a thorough understanding of the physics as well as the chemistry of cometary atmospheres and ionospheres. Such velocity and energy measurements are difficult, but somewhat less so for the ionized species.

In order to achieve Objectives (2) and (3) it is important to determine the ionization mechanisms, with special attention given to the extent to which photoionization is augmented by electron bombardment, collision with hot dust grains, and a variety of plasma processes. The mechanisms and extent of heating and cooling processes and the acceleration mechanisms of the various neutral and ionized species need to be studied; measurements by the proposed ion mass spectrometers are especially likely to make meaningful contributions in this area of energetics and solar wind interaction.

C. INSTRUMENTATION

1. Neutral Mass Spectrometer for Tempel 2 Rendezvous

A thorough analysis of atmospheric gases should be carried out by a neutral mass spectrometer following rendezvous with Tempel 2. A search list for cometary gases is given in Table 2-1, which was compiled, in part, from Delsemme (Icarus, Vol. 24, p. 95, 1975) and Giguere and Huebner (Astrophys. J., Vol. 223, p. 638, 1978). Additionally, molecules in the range 80 to 200 amu, corresponding to aromatic hydrocarbons and other complex molecules have been identified in the Murchison meteorite (Hayatsu et al., Geochim. Cosmochim. Acta, Vol. 41, p. 1325, 1977) and thus might be expected to exist in a cometary nucleus. The nominal mass range of a mass spectrometer should hence include the isotopes of Xenon; e.g., a scan range from 1 to 140 amu is desirable. It would also be valuable to scan to higher masses up to approximately 250 amu occasionally for survey and exploration. The resolution should be sufficient to separate constituents with a mixing ratio of 10^{-4} at adjacent mass numbers ($\Delta m = 1$ amu) in the nominal mass range. A poorer resolution is acceptable for exploring the higher mass range.

Ideally, the neutral mass spectrometer should measure the velocities as well as the abundances of atoms and molecules; such data would yield valuable information on the sources of the species and on the chemical reactions occurring in the atmosphere. The processes that break up the parent molecules mostly yield excess energy, and therefore increase the flow velocity in the coma. Quite high velocities can be

Table 2-1. A Search List for Cometary Gases. Species ($\log_{10}$ of Abundance, Normalized to $\log [H_2O] = 10$)

Mass	Species (abundance)	Mass	Species (abundance)
1	H(10)	24	C_2(8)
2	H_2(8), D(6)	25	$^{12}C^{13}C$(6), CCH(6)
3		26	CN(8), C_2H_2(6)
4	He(4)	27	HCN(8)
5		28	CO(10), N_2(9), C_2H_4(6)
6		29	CH_2NH(7), HCO(6)
7		30	H_2CO(8), NO(7), C_2H_6(5)
8		31	CH_3NH_2(7), HNO(6)
9		32	S(8), CH_3OH(7), $NH_2 \cdot NH_2$(?), O_2(6)
10		33	
11		34	H_2S(8)
12	^{12}C(8)	35	
13	CH(7), ^{13}C(6)	36	C_3(7)
14	N(7), CH_2(8)	37	
15	NH(7), ^{15}N(5), CH_3(7)	38	
16	O(10), CH_4(9), NH_2(7)	39	K(6)
17	NH_3(9), OH(10)	40	$CH_3 \cdot C \cdot CH$(7), Ca(?), Ar(4)
18	H_2O(10), ^{18}O(7)	41	CH_3CN(7)
19		42	CH_2CO(5), NH_2CN(5)
20	Ne(4)	43	HNCO(7), H_2NCN(7)
21		44	CS(7), CO_2(8), $CH_3 \cdot CH \cdot O$(7)
22		45	$NH_2 \cdot CH \cdot O$(6), $CH_3 \cdot NH \cdot CH_3$(6)
23	Na(7)		

Table 2-1. (Cont'd)

Mass	Species (abundance)
46	$HCO \cdot OH$(7), H_2CS(8), $CH_3 \cdot NH \cdot NH_2$(6), NS(8), C_2H_5OH(7), CH_3OCH_3(7)
47	
48	C_4(6), SO(6)
49	C_4H(6)
50	C_3N(6)
51	$CH \cdot C \cdot CN$(6)
52	Cr(4)
53	$CH_2 \cdot CH \cdot CN$(6)
54	
55	Mn(4), $CH_3 \cdot CH_2 \cdot CN$(6)
56	Fe(5), C_4H_8(6)
57	
58	Ni(4)
59	Co(4)
60	OCS(5), $CO(NH_2)_2$(4), CH_3OOCH(5)
61	$NH_2 \cdot CO \cdot OH$(6)
62	
63	
64	S_2(8), SO_2(7)
65	Cu(4)
66	$^{34}SO_2$(5)
72	C_5H_{12}(5)
75	NH_2acid(5), HC_3N(6)
84	Kr(6)
99	HC_7N(6)
123	HC_9N(6)
132	Xe(7)

attained. For example, the photodissociation of CO into C and O typically yields excess velocities of $\sim$5 km/s (both atoms in the ground state). Ultraviolet observations of comets have been interpreted to suggest that there are several velocity components of H atoms. The following velocity components of neutral gas are expected (in a reference system fixed in the comet):

(1) Thermalized heavy molecules with velocities $\leq$1 km/s.

(2) Radicals and atoms with a very similar velocity, $\sim$1 km/s.

(3) Atoms with velocities of up to $\sim$5 km/s from dissociation processes. Also, molecules ejected in jets with speeds ranging up to several kilometers per second.

(4) A minor component of "thermalized" hydrogen atoms of about 4 km/s.

(5) Hydrogen atoms with velocities $\geq \sim 7$ km/s.

We consider the measurement of the velocity distribution of the neutral gas only a secondary objective because of the significantly higher instrument complexity required.

Mass spectrometry for analysis of neutral gases close to the comet (several kilometers to $\sim 10^3$ km from the nucleus) appears to be practical with currently available techniques. Instruments operating in similar gas density regimes employing RF filter or magnetic sector analyzers have been used on the Atmospheric Explorers, Viking, Pioneer Venus, and other missions. All major and a number of minor constituents of the upper atmospheres of Earth, Mars, and Venus have been identified by such instruments. Absolute concentrations and ratios of isotopes of major constituents have been measured. Typically, these instruments have a mass range from 1 to 60 amu. Instruments developed for atmospheric entry probes on Venus and Jupiter are available with a higher mass range, e.g., 1 to 250 amu. Hence, an increase to higher mass ranges for the Halley/Tempel 2 presents no severe problems.

The lower density limit for detection of any species is determined by the instrument sensitivity, associated signal statistics, and detector noise. A secondary electron multiplier can be expected to have a background counting rate on the order of one count per minute, if the detector is carefully life-tested in the laboratory before flight. In order to estimate the instrument performance, the density of gas expected as a function of time and distance from Tempel 2 (R. Newburn, Models of P/Tempel 2, JPL Pub. 79-60, to be published) has been combined with a sample post-rendezvous trajectory to yield the plot of density versus time shown in Figure 2-1. Typical ion source sensitivities for electron-impact ionization are on the order of 10^{-2} to 10^{-3} counts/s per particle/cm^3. A conservative value of 1×10^{-3} s^{-1} cm^{-3} was assumed to convert the densities in Figure 2-1 to counts/minute shown on the right-hand scale of the figure. During the later phase of the mission, even trace constituents (1 part in 10^4) can be measured with an accuracy of 10 percent with only 1-min integration, if the nominal model is correct.

Any mass spectrometer, even under the cleanest laboratory conditions or after a long-duration space flight, will show residual gases desorbing from surfaces in the vicinity of the ion source. Of particular concern are H_2, CO, CO_2, and H_2O which are expected in the coma of a comet and are also commonly observed background gases. Typical background gas densities after instrument bakeout are on the order of 10^2 to 10^3 particles/cm^3 each for CO_2, CO, CH_4, and H_2O and approximately 10^4 particles/cm^3 for H_2. Essentially no background exists for the noble gases, nitrogen and the radicals, although products of radicals may appear at other mass numbers after surface collision; e.g., OH forms H_2O with surface adsorbed hydrogen and O forms CO_2 with surface adsorbed CO.

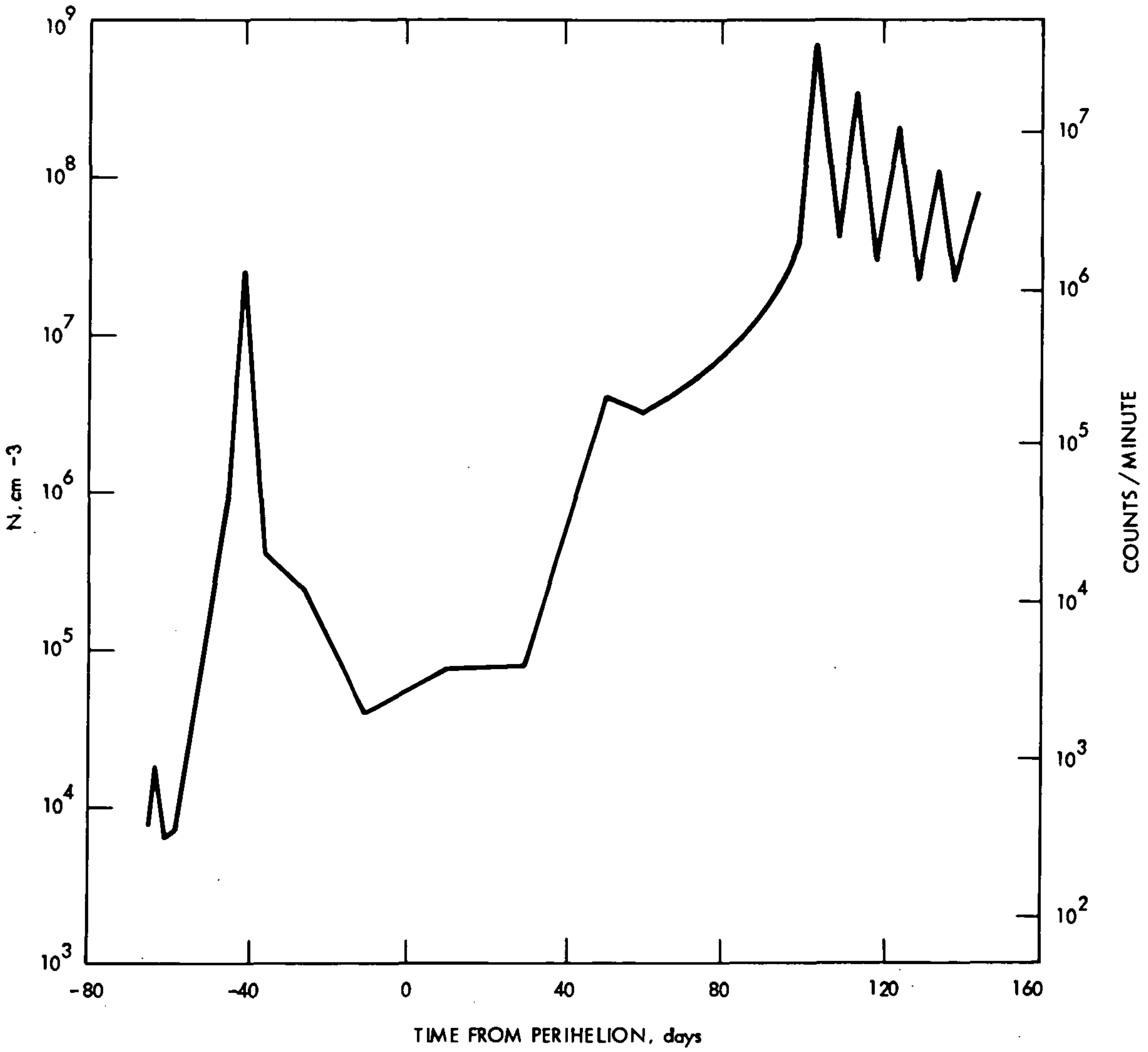

Figure 2-1. Gas Density and Counting Rate of Neutral Mass Spectrometer Expected at Tempel 2

Outgassing can be reduced by using a semi-open ion source, thereby exposing the surfaces to space for effective pumping. As the rate of desorption is strongly temperature dependent, the ion source surfaces may be cooled actively when measurements are made. Low power and thermally isolated filaments for electron emission further minimize outgassing. On the other hand, source heating should be used before encounter and between measurements for rapid clean-up of adsorbed gases. Such clean-up techniques have been used successfully in the laboratory at modest power levels (e.g., $\leq$ 10 W for 500°C source temperature).

Ordinarily, a mass spectrometer measures both incoming particles and particles reflected from the walls of the ion source. Losses occur because of adsorption of incoming particles such as H_2O and CO_2 on the walls and because of chemical reactions of even moderately reactive species such as H_2S and CO. It is possible to study reactive species by using molecular beam techniques which avoid distortions due to gas surface interaction in the ion source elements and on the filament. Separation of beam particles from the surface-reflected gases can be achieved by mechanical chopping or, when the vehicle velocity is larger than the thermal velocity of the gas, energy retarding after ionization can be used to discriminate between surface-reflected and free streaming particles. As the mean free path of the gas molecules is much larger than the distance between the spacecraft and the nucleus, the nucleus resembles a point source subtending only a small angle. (For example, at 100-km separation, the solid angle subtended by the nucleus is approximately 10^{-3} steradian.) Ordinarily, operation of a mass spectrometer in a beam mode results in a loss of sensitivity of a factor of $\sim 10^2$. However, because the motion of the cometary gas is highly anisotropic, forming a beam in the radially outward direction, there will not be a severe sensitivity penalty so long as the axis of the instrument is pointed within 10 deg of the nucleus.

Within a mass spectrum, different gases may appear at the same mass number, e.g., CO and N_2, or have fractionation products which interfere with other gases, e.g., H_2O, NH_3 and CH_4. Several different electron accelerating potentials for the ionizing electron beam can be used to change the fractionation pattern to identify otherwise overlapping species. This technique is common in the laboratory and has also been used on several flight experiments. During a Tempel 2 mission, ample time is available to use this tool effectively for separation of gases like H_2O, NH_3, CH_4, CO and N_2, hydrocarbons and others. Generally the electron energy is about 70 eV for maximum ionization efficiency. Substantial changes in fractionation occur between 20 and 25 eV. Most of the parent peaks show a drop in intensity of about a factor of 2, which is acceptable according to the previous discussion. In Table 2-2 the major constituents (mixing ratio $\geq 10^{-4}$) selected from the estimate given in Table 2-1 are listed. The relative concentrations are normalized to H_2O, which is assumed to have an absolute concentration of 10^6 per cm^3. The molecular mass and the mass numbers at which fractionation peaks occur are also listed. Except where noted, isotope contributions are excluded. The average ion count rates are given for the parent peak assuming a sensitivity of 1 x 10^{-3} counts/s per particle/cm^3 for the ambient gas. The last column in Table 2-2 shows the integration time

Table 2-2. Summary of Neutral Atmospheric Species Expected at Tempel 2 with Abundances Greater than 10^{-4} Times Water

Constituent	Mass Number	Fragmentation Peaks	Relative Abundance 100 km from Nucleus $\log[H_2O] = 6$	Average Count Rate Per Second	Sampling Time for 10% Uncertainty, s
H	1		6	1000	0.1
H_2	2	1	4	10	10
D	2		2	0.1	1000
^{12}C	12		4	10	10
CH	13	12,1	3	1.0	100
^{13}C	13		2	0.1	1000
N	14		3	1.0	100
CH_2	14	13,12	4	10	10
NH	15	14	3	1.0	100
CH_3	15	14,13,12	3	1.0	100
O	16		6	1000	0.1
CH_4	16	15,14,13,12	5	100	1.0
NH_2	16	15	3	1.0	100
NH_3	17	16,15,14	5	100	1.0
OH	17	16	6	1000	0.1
H_2O	18	17,16	6	1000	0.1
^{18}O	18		3	1.0	100
Na	23		3	1.0	100
C_2	24	12	4	10	10
$^{12}C^{13}C$	25	Below detection level	2	0.1	100
C_2H	25	Below detection level	2	0.1	1000

Table 2-2. (Cont'd)

Constituent	Mass Number	Fragmentation Peaks	Relative Abundance 100 km from Nucleus $\log[H_2O] = 6$	Average Count Rate Per Second	Sampling Time for 10% Uncertainty, s
CN	26	14,12	4	10	10
C_2H_2	26	Below detection level	2	0.1	1000
HCN	27	26,15,14, 13,12	4	10	10
CO	28	16,14,12	6	1000	0.1
N_2	28	14	5	100	1.0
C_2H_4	28	Below detection level	2	0.1	1000
CH_2HN	29	28,27,26, 14,12	3	1.0	100
HCO	29	28,16.12	3	1.0	100
H_2CO	30	29,28,16, 14,12	4	10	10
NO	30	16,15,14	3	1.0	100
CH_3NH_2	31	32,31,30,29 28,27,26	3	1.0	100
HNO	31	Below detection level	2	0.1	1000
S	32		4	10	10
CH_3OH	32	32,31,30, 29,28	3	1.0	100
O_2	32	Below detection level	2	0.1	1000
H_2S	34	33,32	4	10	10
C_3	36	24,12	3	1.0	100

Table 2-2. (Cont'd)

Constituent	Mass Number	Fragmentation Peaks	Relative Abundance 100 km from Nucleus $\log[H_2O] = 6$	Average Count Rate Per Second	Sampling Time for 10% Uncertainty, s
K	39		2	0.1	1000
$CH_3 \cdot C \cdot CH$	40	39,38,37,36 26,25,13,12	3	1.0	100
CH_3CN	41	40,39,29,28 27,26,15	3	1.0	100
HNCO	43	42,29,28,15, 14	3	1.0	100
H_2NCN	43	28,27,26, 14,12	3	1.0	100
CS	44	32,12	3	1.0	100
CO_2	44	32,28,22, 16,12	4	10	10
$CH_3 \cdot CH \cdot O$	44	44,43,42,41, 30,29,28,27, 26	3	1.0	100
$NH_2 \cdot CH \cdot O$	45	Below detection level	2	0.1	1000
$CH_3 \cdot NH \cdot CH_3$	45	Below detection level	2	0.1	1000
$HCO \cdot OH$	46	45,44,30,29, 28,17,16,13, 12	3	1.0	100
H_2CS	46	44,32,12	4	10	10
NS	46	32,14	4	10	10
$CH_3 \cdot NH \cdot NH_2$	46	Below detection level	2	0.1	1000
C_2H_5OH	46	45,43,31,29, 28,27,26,15	3	1.0	100

Table 2-2. (Cont'd)

Constituent	Mass Number	Fragmentation Peaks	Relative Abundance 100 km from Nucleus $\log[H_2O] = 6$	Average Count Rate Per Second	Sampling Time for 10% Uncertainty, s
C_4	48	Below detection level	2	0.1	1000
SO	48	Below detection level	2	0.1	1000
C_4H	49	Below detection level	2	0.1	1000
C_3H	50	Below detection level	2	0.1	1000
CH•C•CN	51	Below detection level	2	0.1	1000
CH_2•C•CN	53	Below detection level	2	0.1	1000
CH_3•CH_2•CN	55	Below detection level	2	0.1	1000
C_4H_8	56	Below detection level	2	0.1	1000
NH_2•CO•OH	61		2	0.1	1000
SO_2	64	48,32,16	4	10	10
S_2	64	32	4	10	10
HC_3N	75	Below detection level	2	0.1	1000
Kr	84	[86,83, 82,80, 78] all isotopes	2	0.1	1000
HC_7N	99	Below detection level	2	0.1	1000
HC_9N	123	Below detection level	2	0.1	1000
Xe	132	[136,134, 131,130, 129,128, 126] all isotopes	3	1.0	1000

required to obtain a measurement with a 10% uncertainty. The identification of species with identical mass number and overlapping cracking fractions presents the greatest difficulties.

Only by careful choice of the ionization energies and the observation of all mass peaks can the individual concentrations be determined as solutions of a set of simultaneous linear equations. Species with lower concentrations which may still be above the detection limit of the instrument, e.g., $NH_2 \cdot CO \cdot O$ or $CH_3 \cdot CH \cdot O$, can probably not be detected because of interference with CO_2, HNCO, CS and other hydrocarbons with higher concentrations. Very complex mass spectra will require post-flight evaluation by trial and error using an identical instrument in the laboratory with a simulated gas composition.

Laboratory calibration systems specifically designed to simulate the cometary environment do not yet exist and must be developed. Presently, a number of low pressure static calibration systems for inert gases exist with accuracies of about ±3 percent. Also, several low density and low velocity atomic and molecular beam systems are available or are under construction.

Dust contamination presents a potential difficulty. Laboratory simulations are being performed to evaluate its effects on the ion source operation and to test the efficiency of dust baffles or deflection schemes. Because the compositions and sizes of the dust particles are not well known, it is necessary to experiment with a large spectrum of materials and particle sizes. Individual dust particles located at critical ion source elements might cause serious electric field distortion and change the sensitivity. The result will depend strongly on the electrical character of the dust, e.g., conductor or dielectric. Another critical area is the ion entrance slit into the analyzer. Blockage by a large particle could result in a loss of sensitivity.

In conclusion, although further work is needed to evaluate the effect of dust on the instrument performance and to develop schemes to prevent or minimize contamination, the basic elements for successful mass spectroscopy near the comet exist. It is reasonable to expect concentration measurements of approximately 20 species. If instrument sensitivity could be further increased, it would also be possible to observe short-duration fluctuations in the gas emission from the nucleus.

2. Neutral Mass Spectrometer for Halley Flyby

During the very short duration of the Halley flyby, there is probably not enough time to study trace elements in the atmosphere; the emphasis must be on the abundance and spatial variation of the major components.

The highest mass peak expected from simple parent species is 64 amu from $^{32}SO_2$, which is likely to be a major repository of sulfur

in comets. As sulfur has been observed in comets (in emission), it is recommended that a probe mass spectrometer have a mass range from 1 to 66 amu, which is the mass of the $^{34}SO_2$ isotope.

Good quality measurements of the major molecules in the coma can probably be made by a neutral mass spectrometer designed to take advantage of the 57-km/s relative velocity. Unconventional mass spectrometer designs do exist which are intended to operate exclusively and very effectively in a beam mode. These devices are conceptually and mechanically simple, and can provide certain advantages such as high sensitivity, reduced background due to outgassing, and no wall interactions.

During the Halley flyby, ions formed from neutrals in the instrument's ion source will have a large, nearly constant velocity regardless of mass. It is therefore only necessary to disperse the ions according to energy, using simple electrostatic analyzers, in order to determine mass. For a velocity of 57 km/s, the kinetic energy is about 17 eV per amu assuming the ions are singly charged. Because of the high relative velocity of the ions produced from ambient gas, it is possible to discriminate against a number of background and interference sources such as: outgassing of the ion source and/or spacecraft, chemical reactions and losses of reactive species in the ion source, and species arising from dust and gas impact on ion source surfaces. Thus, good mass spectra of cometary gases can be obtained with little or no degradation caused by dust.

A major question, concerning any fast-flyby neutral mass spectrometer, is sensitivity. Narrow slits are not required by electrostatic analyzers. The relatively large entrance apertures, coupled with very high transmission factors, allow sensitivities which, conservatively, can be on the order of 0.1 counts/s per molecule/cm^3, or about 100 times higher than with conventional instruments. Assuming, for example, mass scanning over two mass ranges, 1-8 and 12-64 amu and eight steps/mass, each scan requires 480 steps. Therefore, the count rate in any single integrated mass peak is 1.5×10^{-3} n counts/s, where n is the species number density in molecules/cm^3. This figure could be increased by sampling fewer masses, by spending less time scanning between masses, or by applying scan strategies under real-time microprocessor control to optimize mass peak dwell time. Allowing for a factor of about four increase in count rate using these strategies, and a miss distance at Halley of 1500 km, where $n \simeq 1 \times 10^6$ cm^{-3}, then about 10^4 counts/s can be expected for the major components. There would be a total of 10^5 counts for the major component over the 10 s nearest closest approach.

Modification of Giguere and Huebner's one-dimensional photochemical model by scaling down the total density by an order of magnitude and including $n(CO) = n(CO_2)$ and $n(N_2) = n(NH_3)$ indicates that such an instrument should be able to detect at least the eight most abundant species (H_2O, CO_2, CO, CH_4, NH_3, N_2, H, and OH). The mass overlap between CO and N_2 and the fragmentation patterns of H_2O, CH_4, and NH_3 can be handled by the variable ionization energy technique discussed for the rendezvous mass spectrometer.

The required mass range and resolution are related to the extent that it should be possible to distinguish adjacent mass units at the upper limit of the mass range. For a mass range of 1 to 66 amu, an energy scan from 16 eV to 1100 eV would be required. Over this range, electric analyzers easily yield 1 percent energy resolution, which corresponds to a mass discrimination well in excess of 1 amu between 1 and 66 amu.

A major requirement for the fast-flyby mass spectrometer is that its fly-through beam axis be oriented no more than ±3 deg from the spacecraft-comet velocity vector. If the spacecraft is spinning, then the spin axis must be aligned with the relative velocity vector to within ±3 deg or better. There should be no major impact on mission strategy other than that the spacecraft should fly within 1500 km of Halley's nucleus; even closer would be better. Beyond this flyby distance, severe constraints would have to be imposed on the mass spectrometer design and sampling strategy in order to accommodate the much lower count rate.

No existing mass spectrometer meets the requirements of the Halley probe. However, there are no fundamental problems to be overcome. Instruments already in use in the laboratory and on rocket flights could be reconfigured to handle the high speed conditions; the effects of high velocity dust impact on instrument operation need further study. It is desirable that, in parallel with the instrument development, a fast-molecular-beam facility be built for the calibration of such instruments; this is not a fundamental problem because well-developed charge-exchange methods can be used to generate the required fast neutral gas beam.

3. Thermal Ion Mass Spectrometers

The measurement of the composition, temperature and velocity of the thermal ($\lesssim$50 eV) ions from the rendezvous spacecraft is necessary to achieve the stated scientific objectives and is feasible using present technology in spacecraft instrumentation. Thermal ion mass spectrometers have been used widely and successfully for nearly three decades for in situ studies of the terrestrial ionosphere (e.g., OGO, Atmosphere Explorer, ISIS) and have now been successfully extended to planetary exploration (Pioneer Venus).

The maximum total ion density for Tempel 2 predicted by M. Neugebauer in 1979, close to the surface near perihelion, is about 5×10^3 cm^{-3} dropping to about 1 cm^{-3} at about 3×10^4 km. Some of the most important and/or abundant ions which are likely to be encountered are listed in Table 2-3. An ion mass spectrometer with a mass discrimination of $\Delta m \leq 1$ amu over a range of 1-100 amu, capable of making measurements over a density range of about 10^{-1} to 10^5 cm^{-3}, is called for. An instrument which can be programmed either to sample in an exploratory mode by stepping through an adjustable mass range or to "sit" on selected mass peaks for energy and flow direction studies is desirable. Ion temperature measurements in the range of 150 to 500,000 K should

Table 2-3. Ions That May Be Present in a Cometary Coma

Mass	Species	Mass	Species
1	H^+	25	
2	H_e^+(solar wind), H_2^+	26	CN^+, $C_2H_2^+$
3	H_3^+	27	HCN^+, $C_2H_3^+$
4	H_e^{++}(solar wind)	28	H_2CN^+ $C_2H_4^+$, CO^+, N_2^+, Si^+
5		29	HCO^+, N_2H^+, $C_2H_5^+$
6		30	NO^+, CH_2O^+, $CH_2NH_2^+$
7		31	CH_3O^+
8		32	S^+
9		33	
10		34	
11		35	
12	C^+	36	
13	CH^+	37	
14	CH_2^+, N^+	38	
15	CH_3^+, NH^+	39	K^+
16	CH_4^+, NH_2^+, O^+	40	Ca^+, CH_2CN^+
17	CH_5^+, NH_3^+, OH^+	41	
18	NH_4^+, H_2O^+	42	
19	H_3O^+	43	CH_3CO^+
20		44	CO_2^+
21		45	HCO_2^+, Sc^+
22		46	
23	Na^+	47	CH_2SH^+, $CH_3O_2^+$
24	Mg^+	48	Ti^+, NH_2S^+

Table 2-3. (Cont'd)

Mass	Species	Mass	Species
------------		58	Ni^+
52	Cr^+	59	Co^+
56	Fe^+	65	Ca^+

also be made by this instrument using either standard retarding potential or differential energy analysis methods; there are techniques available for flow velocity measurements which work over the anticipated range of parameters (≲50 eV).

The one important aspect of cometary ionospheres which is different from planetary ionospheres is the presence of a significant dust flux. This is not expected to cause serious problems because the ions are deflected in the instrument, while the dust can be either collected in a dust trap or made to fly through the instrument; however, any associated impact ionization products may cause some difficulties. Studies to evaluate the general problem of the expected dust fluxes on mass spectrometry are underway. The surface outgassing phenomenon, which is a significant consideration in the design and operation of a neutral mass spectrometer, does not cause any interference in the normal operation of an ion mass spectrometer. The mass number ambiguity discussed in the section on rendezvous neutral mass spectrometers is also present in ion mass spectrometry, with no single and practical resolution available. The two most likely and important ions which have mass overlap are N_2^+ and CO^+, and the resolution of this difficulty will have to be left to other methods (e.g., optical spectrometry).

The technology and experience do exist to produce a thermal ion mass spectrometer which meets the needs just outlined. Although there is no unit "on the shelf" which could be used unchanged for the rendezvous mission, the modifications required are small. Similar instruments flown on Dynamics Explorer, Pioneer Venus, SCATHA, etc., provide the necessary confidence that a thermal ion mass spectrometer, capable of making the needed measurements within the mission constraints, will be available for the Halley/Tempel 2 mission.

4. Energetic Ion Mass Spectrometers

Both the high speed of the Halley flyby and the intrinsic speeds of some cometary ions require mass spectrometers for energetic as well as for thermal ions. Cometary ion fluorescence profiles have been explained using simple models with an initial, radial ion velocity of 3 to 5 km/s.

Tailward velocities in the range 10 to 40 km/s have been observed in the antisolar hemisphere. Far from the nucleus, cometary ions that have been picked up by the solar wind will have speeds of 400 km/s or higher. Cometary ions with even higher velocities, corresponding to energies up to 100 keV, cannot be ruled out.

The ions probably flow roughly radially away from the comet at small distances from the nucleus and away from the sun at very large distances. In between, the flow pattern is more complicated and uncertain. For the Halley flyby, the expected speeds are obtained by taking a vector sum of the speeds in the comet's reference frame and the flyby speed of 57 km/s.

The requirements for an energetic ion mass spectrometer at Halley and Tempel 2 are given in Table 2-4. The upper mass range for the Halley flyby was chosen as 45 amu (HCO_2^+) because so little time is available for scanning over many different masses. The upper velocity limit was rather arbitrarily chosen to give some overlap with probable solar wind experiments.

At Tempel 2 where long integration times are possible, sensitivity is not a problem. Dust will probably not be a serious problem because most fast ion mass spectrometers deflect ions either electrostatically or magnetically before detection whereas the dust particles with their much larger mass/charge ratio will not be deflected enough to reach the detector. We expect that instruments can be designed to avoid blockage of thin slits by dust.

The electron and ion density distributions at Halley at the time of the flyby are expected to be $\geq 10^6/r(\mathrm{km})\ \mathrm{cm}^{-3}$ (R. Newburn, in CHSWG Report, 1977). Thus, the total ion fluence during a flyby with a miss distance of 10^3 km should be $\geq 10^{12}\ \mathrm{cm}^{-2}$. To obtain 10^4 counts of a 1 percent constituent, the product of instrument efficiency (or duty cycle for a given mass) times aperture area must be $\geq 10^{-6}\ \mathrm{cm}^2$. This is almost certainly achievable for a fairly "smart" instrument with efficient cycling through masses, energies, and angles of incidence.

At a flyby speed of 57 km/s, the probe will probably travel several thousand kilometers per measurement cycle. As this distance is greater than the scale size of observed plasma inhomogeneities, there is bound to be aliasing and distortion of the data, the effect of which can be alleviated somewhat by making normalizing measurements such as electron density or magnetic field strength with a time resolution of about 1 s. Some of the more important masses should be sampled more frequently than others to ensure acquisition of relevant data within a few thousand kilometers of the nucleus.

Finally, consideration must also be given to the ions created when dust particles impact the spacecraft or its instruments. At a relative speed of 57 km/s, approximately one ion is created per incident atom of dust. Using Newburn's dust mode, we calculate that dust impacts will create ions at a rate of $1.7 \times 10^{20}/r(\mathrm{km})^2\ \mathrm{s}^{-1}$ per cm^2 of target material. Because this is many orders of magnitude greater than

Table 2-4. Requirements for an Energetic Ion Mass Spectrometer

Parameter	Halley	Tempel 2
Mass range, amu	1 to 45	1 to 100
Mass discrimination, amu	≤ 1	≤ 1
Energy range	$\sim$10 eV to 10 keV	$\sim$10 eV to 10 keV
Look direction	From velocity vector to sun	From comet to sun
Time resolution	Seconds or minutes	Minutes or hours
Gas density, cm^{-3}	1 to 10^5	1 to 10^4

the flux of natural cometary plasma, care must be taken to separate the two plasma components. The separation can be made on the basis of velocity because the dust-created plasma will be nearly at rest in the spacecraft reference frame.

Energetic ion mass and velocity spectrometers have been flown on the ISEE and GEOS spacecraft and are scheduled for Galileo and the International Solar Polar Mission. Although none of these instruments meets all the requirements given in Table 2-4, NASA is currently supporting three programs for the development of suitable instruments. There are no fundamental problems to be solved; the principal task is to determine the optimum configuration of electrostatic analysis plus either magnetic or time-of-flight analysis to meet the requirements of this specific mission. There is no doubt that an instrument can be ready in time for the comet mission.

SECTION IV

REPORT OF THE IMAGING SUBGROUP

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A. INTRODUCTION: IMAGING ON THE HALLEY/TEMPEL 2 COMET MISSION

The concept of an imaging experiment for the Halley/Tempel 2 comet mission presents some difficult and distinctive challenges not normally encountered in flyby or orbital missions to planets. The most basic challenge is that the prime target of the mission, the nucleus of Tempel 2 (or any other cometary nucleus for that matter), has never been resolved by any measurement technique; thus, all knowledge about it is purely circumstantial. We are therefore designing a camera system and estimating the expensive logistics required to support it with only vague estimates of the global physical and chemical properties of the target.

Another almost equally far-reaching challenge is the enormous range of linear scales and brightness with which we must contend. For example, the imaging experiment has significant scientific objectives concerning the cometary nucleus, an object a few kilometers in size which will probably require spatial resolutions approaching the meter range; objectives concerning structures in the coma whose dimensions range from 10^2 to 10^5 km; and objectives concerning structures in the tail whose linear scales range from 10^3 to 10^7 km. The range in surface brightness that must be faced in the wavelength interval 3000 to 10,000 Å ranges from roughly 13 W/m^2 sr for the resolved nucleus, to 1.9 x 10^{-2} W/m^2 sr for the central coma, to 1.9 x 10^{-3} W/m^{2}sr for the gas and dust tail some 4 x 10^6 km from the nucleus. The gas tail

might constitute 10 to 50 percent of this brightness at 1.53 AU. When these diverse conditions are coupled with an almost equally large range of distances over which imaging must be performed ($\geq 10^5$ km at Halley to perhaps as close as 10 km in the final phases of the Tempel 2 rendezvous), the profound impact on imaging hardware and experiment strategy is apparent.

Other new challenges exist. Both probe and rendezvous imaging systems must operate within the atmosphere of the comet and face any environmental hazards associated with dust and gas outflowing from the nucleus. The relationship of imaging to other experiments on the spacecraft is perhaps closer than in any previous mission; for example, in conjunction with radar altimeter and accelerometer measurements, imaging data will be crucial to the determination of the bulk density of the nucleus of Tempel 2. In addition, the rendezvous imaging system must provide navigation information enroute to the Halley Flyby and Tempel 2 Rendezvous, as well as frequent information on the state, location, and level of activity of the nucleus of Tempel 2 as part of an adaptive mission strategy and as an aid to the interpretation of other experimental data (e.g., mass spectrometry, dust collection and analysis, remote chemical mapping). Similar challenges face the designer of the camera system for the Halley probe. The designers must ensure the return of accurate information on the trajectory of the probe relative to the nucleus of Halley so that the various in situ measurements can be correctly interpreted.

In response to the challenges outlined above and also certain specific imaging scientific objectives, which will be discussed subsequently, the Imaging Subgroup has arrived at a conceptual design for plausible rendezvous and probe camera systems which we recommend be included in the payload of the Halley/Tempel 2 mission. The rendezvous system consists of a twin framing camera system, with three fixed focal lengths and two, large format, UV-enhanced, solid-state silicon detectors. The probe camera is a fixed focal length, electronically "smart", spin-scan system based on a solid state, silicon, line array detector.

B. NATURE OF THE IMAGING TARGETS

1. Halley

When planning an imaging experiment, it is of considerable interest to have as much prior knowledge as possible regarding the nature and extent of the target. In the case of Comet Halley, whose last apparition occurred in 1909-1910, we refer to the extensive study by N. T. Bobrovnikoff (Publication of the Lock Observatory, Vol. 7, p. 309, 1931) for indications of the most likely state which the comet might be in during the proposed flyby in late November 1985, some 73 days before perihelion passage. The equivalent time during the 1910 apparition was early February 1910. Figure 3 of Bobrovnikoff's study shows a photograph of the comet at this time. The comet had already developed a slender, but "kinky" tail (presumably this was an ion tail)

about 0.5 to 3 million km long. The aspect of the comet and its tail changed daily, presumably indicating rapid changes in activity at the nucleus and in the interplanetary medium. Several fine streamers were observed as well as a rather definite "jet" (perhaps 10^5 km long) embedded in an essentially spherical coma (100,000 to 200,000 km in diameter) which also featured several concentric envelopes and at least two "emission fans" ($\sim$ 30,000 km long). The "nucleus" apparently showed a "granularity" in its structure (perhaps indicative of multiplicity), and occasionally showed rapid fluctuations in brightness. The spectrum of the comet showed both a continuum of the solar type, presumably indicative of dust in the coma, and strong emissions of a variety of neutral molecules (predominantly CN and C_2) that are usually associated with comets.

It appears certain, therefore, that we can expect Halley to exhibit considerable activity during the time of the flyby and the descent of the probe to the nucleus. An ion tail will most probably be present, and the inner coma should show a variety of definite and changing substructures. The nucleus referred to above is really the innermost volume of the coma (perhaps 2000 to 3000 km in diameter); however, if the reports of the 1910 apparition can be taken at face value, we can expect considerable heterogenity and variability at this scale.

Finally, it is of considerable interest to know what obscuration of the nuclear regions might be present owing to the liberation of dust particles into the coma. Only very rough estimates can be made but, on the basis of the best available models (R. Newburn, Models of P/Tempel 2, JPL Pub. 79-60, to be published), Z. Sekanina conservatively estimates an optical depth in dust down to the nucleus on the order of 0.1 or possibly less.

2. Tempel 2

The estimated diameter of the nucleus of Tempel 2 (R. Newburn, Models of P/Tempel 2, JPL Pub. 79-60, to be published) is 3 km, roughly half the size of Comet Halley. The atmospheric and tail activity of the comet is, however, far less than that of Halley. Although CO^+ ions have been seen in its spectrum, there have been no reports of a developed plasma tail in the 16 apparitions it has been observed. The spectrum also shows the presence of neutral molecules and perhaps dust in the coma. On photographs, however, the coma is poorly developed, exhibiting only a faint indication of an "emission fan" emanating roughly in the solar direction.

The comet is variable in brightness (a flare-up of $\sim$1 mag was observed in early 1979 when the comet was at a heliocentric distance of 3.2 AU), especially for a few months surrounding the time of perihelion passage. In appraising the observed behavior of Tempel 2, Sekanina notes that the anisotropy of the outgassing probably implies that the nuclear surface has a complicated structure, presumably disintegrating slowly under the action of incident sunlight.

The very different behavior exhibited by Halley and Tempel 2, even at the same heliocentric distance, points to major differences between their two nuclei; these differences may be the result either of real differences in the physical and chemical structures of the two bodies, or may simply reflect a very different state of evolution in two comets that otherwise would be physically and chemically similar.

C. SCIENCE OBJECTIVES FOR THE IMAGING EXPERIMENT

The science objectives for the imaging experiment, as recommended by the Imaging Subgroup are given below.

1. Rendezvous Spacecraft

(a) Determine the bulk characteristics of both cometary nuclei, including their sizes, shapes and rotational properties.

(b) Characterize the chemical and physical diversity of the nucleus of Tempel 2 through measurements of its color, albedo, roughness, and texture.

(c) Characterize the degree of activity on the nucleus of Tempel 2 and the evolution of its surface.

(d) Relate the activity on the nucleus of Tempel 2 to its surface morphology and chemical composition.

(e) Characterize the relationship of the surface activity of both comets to their atmospheres and their evolution.

(f) Determine the geometrical structure and dynamical behavior of Halley's tail and determine the relationship of tail structures to activity on the nucleus.

2. Halley Probe

(a) Locate the position of the nucleus in relation to the probe trajectory.

(b) Characterize the bulk properties of the nucleus and its state of activity at the time of encounter and make comparisons with the nucleus of Comet Tempel 2.

Objectives (1) (a-d) and (2) (a-b) refer to the prime mission objective, which addresses the study of the physical and chemical state of the cometary nucleus. Objectives (1) (e-f), which deal with the study of atmospheric and tail phenomena, should apply primarily at Comet Halley during the flyby. However, there may be some application

of (1) (e) at Tempel 2 depending on the level of activity found to be present during the mission.

Underlying all of these objectives is a strong relationship between imaging and other more specific experiments included in the rendezvous and probe payloads and Earth-based observations. For example, in Objective (1) (a), the rendezvous imaging experiment should achieve sufficient precision (we recommend that the accuracy in linear dimensions should exceed 3 percent) in the measurement of size and shape so as to yield, together with the mass determination experiment, a well determined bulk density. Similarly, in (2)(a), the probe camera system should be capable of reaching a sufficient precision in determining the probe trajectory so that in situ atmospheric sensors can relate their measurements accurately to sources at the nucleus (or nuclei). The actual precision required needs further study.

D. IMAGING EXPERIMENT STRATEGY

In arriving at a strategy for the performance of the Halley/ Tempel 2 imaging experiment, as well as for the conceptual design of the hardware, the Subgroup has taken the following general factors into consideration:

(1) Possibility of a dust hazard to the rendezvous camera system at Tempel 2.

(2) Requirement for optical navigation during the rendezvous maneuvers.

(3) Requirement that imaging be part of an adaptive mission capability and provide timely information on the status of activity on the nucleus.

(4) The requirement that long periods of the rendezvous will be spent making measurements very close (100-10 km) to the nucleus.

(5) The availability of good Space Telescope and Earth-based observing conditions during the Halley flyby and the early rendezvous phase.

(6) The requirement that the rendezvous spacecraft encounters Halley at a large distance (10^5 km).

(7) The substantial probability that the cometary environment will be very heterogeneous and that the shape of the nucleus will not be even approximately spherical.

These factors have been considered in conjunction with various performance requirements (outlined below), which we believe to be appropriate, to arrive at the following conclusions regarding imaging experiment strategy.

(a) Halley's nucleus should at least be "resolved" from the rendezvous spacecraft. For an estimated 5 km diameter for the "nucleus", a camera system that can provide 1 or 2 km per line pair from the minimum encounter distance (10^5 km) is adequate.

(b) For a comparative study of the nuclei of Halley and Tempel 2, a probe camera system is required which can provide at least one picture of the nucleus of Halley at a spatial resolution which might reveal clues regarding its physical state. In our judgment, images that exceed a resolution of 250 m per line pair would be of great value in this context.

(c) A spatial resolution in the range 5 to 50 km per line pair seems reasonable to investigate the nature of structures in the inner coma of Halley from the rendezvous spacecraft. Also, as the structure of coma features is three-dimensional and develops in time, an attempt at stereoscopic coverage is recommended, in conjunction with the wide field/planetary camera on Space Telescope. The camera on the Space Telescope will have an appropriate resolution between 36 and 60 km per line pair at Halley in the 30 days following Halley encounter. Coma structures may or may not have characteristic spectral emissions associated with concentrations of molecules. The imaging system cameras should have a range of suitable spectral bandpasses to investigate this.

(d) In order to investigate the morphology of tail structures and obtain some indication of their development in time and space, the rendezvous imaging systems will require a fast, wide-field camera capable of imaging in the characteristic ion emissions associated with comet tails. A system with a field of view of about 3 deg should be adequate if the tail activity during Halley flyby is similar to the experience of 1910. This experiment should be performed in conjunction with telescopic observations from the ground (the Space Telescope camera field of view is probably too small) to obtain stereoscopic information. Good coverage from the ground will probably require the formation of a coordinated observing network. The best time for stereoscopic observations is during the approximately 50 days following the Halley encounter.

(e) At rendezvous, the prime imaging objectives seem to divide conveniently into four distinctive measurement categories:

  (1) Measurements of the bulk characteristics of the nucleus (dimensions $\sim$3% accuracy, rotational properties).

(2) Investigation of the physical diversity of the surface of the nucleus (color boundaries, albedo, texture, activity centers).

(3) Investigation of the surface morphology of the nucleus (to resolutions approaching 1 m per line pair).

(4) Long-term (approximate months) monitoring of any centers of activity that exist on the nucleus to help establish the mode of evolution of the surface of the nucleus.

In any practical scheme, the last three categories must be accomplished from distances relatively close to the nucleus deep within the comet's dusty atmosphere. Although it seems feasible to overcome any potential dust hazards to the imaging hardware (a study of possible methods to protect the cameras from dust is presently underway) in light of the uncertainties of the cometary environment, it is wise to formulate a strategy in which most basic properties of the nucleus are obtained near the time of the initial rendezvous before entering the dusty regions of Tempel 2's atmosphere. This strategy requires that the hardware be capable of resolving the nucleus to a linear scale of about 100 m per line pair from distances that could range from 2,000 to 20,000 km depending on the degree of activity found.

(f) Throughout the rendezvous mission, the imaging hardware should be capable not only of providing high spatial resolution (down to 1 m per line pair) measurements of the physical state of the surface of the nucleus, but also of simultaneously providing a global view of the nucleus and its general state of activity. Such a capability is also needed to provide navigation information with respect to the presumably non-spherical nucleus. Practical limitations on the dimensions of available detectors require an imaging hardware strategy which combines telescopes of very different focal lengths. For example, much of the extended (120 days) post-perihelion reconnaissance phase and the subsequent 150-day nucleus orbit phase is spent at ranges between 50 and 500 km, which implies a field-of-view capability of about 4 deg for maintaining adequate global coverage. It is not possible with present detectors to simultaneously achieve this field of view in combination with previously discussed linear resolutions in a single telescope of fixed focal length. Thus, the above requirements call for a hardware strategy that uses a multiple focal length camera system.

E. IMAGING HARDWARE CONCEPTS

1. The Detectors

The sensitivity, large format, wide spectral range and photometric and geometric stability of the 800 x 800 Texas Instruments/JPL charge-coupled device make it the only major candidate for the imaging sensor on the rendezvous mission. This detector has pixels which are 15 μm square. It is expected (see the reports of the Remote Sensing Subgroups) that color imaging of the cometary nucleus in the near ultraviolet (at wavelengths greater than 1800 Å), as well as in the visible spectrum, will reveal diagnostic information on minerals present on the surface of the nucleus; also coma gases have distinctive emissions in the ultraviolet. We therefore recommend the ultraviolet-enhanced version of this detector such as is being developed for application in the wide-field/planetary camera on the Space Telescope.

The Halley probe is spin-stabilized and a square detector format is not especially advantageous to the probe camera. The Imaging Subgroup has stimulated work from two independent groups on conceptual designs for a probe camera that is being used as an input to a study by the European Space Agency. Both of these efforts agree that some type (there are several available) of solid-state, silicon-based, linear array would make the most suitable detector in this case.

2. Rendezvous Camera System

The requirements and experiment strategy outlined in the preceding sections coupled with the specifications of the detector system are sufficient to define the optical characteristics of the cameras. The strategy at Tempel 2 and the resolution of Halley's nucleus from a distance of 10^5 km will require optics with a focal length of about 3 m. The detector format restricts the field of view of this optical system to 0.23 deg. The field of view requirements during the post-perihelion reconnaissance and the subsequent nucleus orbit phase at Tempel 2, plus the ability to perform stereoscopic measurements of the kinematics of Halley's ion tail, require a second optical system of about 140-mm focal length (5-deg field of view). Finally, the requirement that the highly detailed, narrow-angle frames of Tempel 2 taken with the 3-m optical system on final approach to the nucleus should be interpretable in terms of larger physical structures on the nucleus requires a third optical system of intermediate focal length. We recommend a focal length of about 600 mm, which gives a ratio of about 4 or 5 to 1 between the fields of view of the three systems. Exclusion of this last system leads to a ratio of 22 to 1 between the fields of view of the narrow- and wide-angle systems. Experience has shown that this ratio would be far too large to ensure the physical interpretability of detailed, high-resolution, images of a surface that is expected to evolve during the mission. (A ratio of 10 to 1 is the largest that has been used in the past; in the opinion of our consultants, this ratio was unsatisfactory.)

The speed (focal ratio) of the camera optics is set by the exposure requirements and must be minimized to reduce the overall

weight of the system. The Subgroup has not investigated exposure requirements in detail, but a preliminary look suggests that focal ratios of roughly f/15, f/12, and f/4 for the 3-m, 0.6-m, 0.14-m optics may be adequate. This matter requires further study as soon as possible. We also recommend that an all-reflecting optical system (rather than the high-performance catadioptric Schmidt-Cassegrain systems that have been used previously) be used in the 3-m and 0.6-m telescopes to enhance their ultraviolet transmission characteristics and to further reduce their weight.

In conjunction with this Subgroup's work, a conceptual study of cameras similar to that described above is being performed by the Space Imaging Systems group at JPL. One attractive system being considered is a twin-camera system (i.e., two detectors) which incorporates three fixed focal lengths. In this system, the 3-m and 0.14-m optics share a common detector through an optical switch. The 0.6-m system is a separate camera. The total weight and power of this system, including electronics, are estimated to be 32 kg and 25 W. Additional serious study of this system is recommended.

Finally, it should be noted that the detector/telescope system outlined is capable of sensing over a very wide spectral range ($\sim$0.18 to 1.0 μm) with considerable sensitivity. The cometary spectrum is a blend of a scattered continuum and highly localized molecular emissions, and there will also be considerable interest in the polarimetric properties of this reflected light. It is therefore very important in the design of the rendezvous camera system to ensure a capability for imaging through a wide selection of spectral and polarizing filters. We estimate that provision should be made for at least 15 to 20 such filter positions.

3. Probe Camera System

Two independent concepts of a probe camera system have been developed by consultants to this Subgroup. Various aspects of these concepts have been incorporated in the current probe payload for the purposes of a detailed study by the European Space Agency.

4. Spacecraft Impacts and Picture Budget

For efficient imaging with a rendezvous camera system similar to that described above, at least the following spacecraft capabilities should be achieved: (1) stable pointing to ±0.1 deg, (2) rapid real-time telemetry intermittently throughout the mission, and (3) minimal operational response time to hazards (hours?).

An adequate picture budget should also be developed. In our study of the imaging requirements, we estimate that a total picture budget of 40,000 frames is probably adequate.

SECTION V

REPORT OF THE SUBGROUP ON REMOTE SENSING OF THE ATMOSPHERE

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A. INTRODUCTION

It is convenient to treat separately the remote sensing of the atmosphere and the nucleus. In the present context, the term atmosphere includes both the coma and the tail. Remote sensing of cometary dust is discussed primarily in Section VI of Part Two. Imaging, an important remote sensing tool for both atmosphere and nucleus studies, has already been discussed in Section IV.

B. OBJECTIVES

Emission and absorption spectroscopy over the wavelength range from the ultraviolet to the thermal infrared has the demonstrated capability of measuring a number of important atoms, molecules, radicals, and ions as a function of distance from the nucleus. Examples are H, OH, H_2O, CO_2, CO, CH_4, and NH_3. Remote sensing can therefore:

(1) Supplement direct sensing for a group of very important molecules.

(2) Compare the two comets Halley and Tempel 2 with the same instruments operating under similar conditions.

(3) Give a baseline and calibration for past and future measurements from Earth and Earth orbit.

C. INSTRUMENTS AND MEASUREMENT TECHNIQUES

All instruments discussed have flown in Earth orbit or on planetary missions, and require only minor adaptations for a comet mission. The principal instruments are an ultraviolet-visible spectrometer

and a set of pressure-modulated radiometers for molecules detectable in the infrared. Both have application to surface studies as well. If a near-infrared mapping spectrometer or millimeter-wave radiometer are flown for solid-body studies, possible applications to the atmosphere should be kept in mind.

1. UV-Visible Spectrometers

This spectral region is already well explored from Earth and spacecraft, and has furnished much of our current physical information about comets. It shows us, albeit in a somewhat selective fashion, the presence and distribution of atoms, molecules, and ions. Prominent among these are H (at Lyman-alpha, 1216 Å) and OH (at 3060 Å), the primary fragments of H_2O. Choice of a long-wavelength limit requires a detailed trade-off between complexity (and weight) and the number of spectral features desired; it is technically feasible to go to around 9000 Å. A short limit between 800 and 1200 Å seems suitable. The choice of range should also take into account reflectance spectroscopy of the nucleus.

It is desirable to use a two-dimensional detector, giving simultaneous measurement of a range of wavelengths and a spatial dimension. Photoelectron-counting detector arrays using microchannel array plates are now becoming available, with up to (1024 x 1024) pixels. These developments allow high spatial resolution in one direction, and high spectral resolution ($\sim$1 Å) with no moving parts and no special requirements for the scan platform. Several detector arrays with different photocathodes will be necessary for achieving a large spectral range, say 1000 to 9000 Å; however, it is feasible to consider only one electronics package to be time-shared by the various detectors. Such an arrangement could be made with a relatively small weight and power penalty, as the electronics package is the largest and heaviest single component. Another two-dimensional instrument has been developed for Spacelab 1 and was proposed for the International Solar Polar Mission. A one-dimensional instrument is flying on Voyager; the spatial dimension is provided by the scan platform, a feasible but far less efficient arrangement, both for observing and data reduction. Scanning instruments have flown on or are planned for many missions, most recently Pioneer Venus and Galileo. The simpler instruments trade operational complexity for smaller mass and lower cost; the trade-off must be made in the context of the whole mission. Mounting on a scan platform is required; operational complexity depends on the version of the instrument that flies.

For studies of the line profile of H (Lyman alpha) and the D/H ratio, it is desirable to carry atomic absorption cells containing H_2 or D_2 and a heated filament for dissociation. Such cells have flown on many missions in Earth orbit and on USSR planetary missions.

The near-infrared spectrometer discussed in Section VII also has some application to atmospheric sensing.

2. Far Infrared

The region above about 5 μm is useful for sensitive measurement of polar molecules, including the important H_2O, CH_4, CO_2, CO, and NH_3. These molecules are those that cause difficulties in the ion source of a mass spectrometer, and infrared measurements would be a valuable supplement during rendezvous, as well as flyby. Both solar absorption and thermal emission could be used, sampling respectively the ground and excited states. It will be desirable to look at both, because local thermal equilibrium is unlikely to exist in most regions of a cometary atmosphere.

The relatively small column densities, even of major molecules, can be detected only with very high spectral resolution, unattainable by the infrared interferometer spectrometers used on past and present Earth, Mars, and Jupiter missions. High-resolution Fourier transform spectrometers have flown on aircraft and balloons, and are being developed for Spacelab, but they are very large and heavy. As the number of applicable gases is small, a set of selective radiometers may be more practical. To attain their selectivity and specificity, they use a cell containing the gas to be detected (see the review by J. T. Houghton and F. W. Taylor, Rep. Prog. Phys., Vol. 36, p. 827, 1973). Two versions (selective chopper radiometer and pressure-modulated radiometer) have flown successfully on Earth satellites, and Pioneer Venus Orbiter had a pressure-modulated radiometer.

These instruments can also be used as thermal radiometers for surface studies of the nucleus. In either mode, their principal use would be during rendezvous; their use in flyby missions needs further study. Scan platform mounting is required.

3. Radio

A millimeter-wave radiometer would be useful for detecting the 183-GHz H_2O line as well as other possible parent molecules such as HCN or CH_3CN.

D. STRATEGY

Many of the prime atmospheric observations can be made at a considerable distance from the comet. In fact, as the name implies, many remote-sensing instruments operate best when relatively far from the comet where they can see the whole picture. Suitable distances range from a few thousand to perhaps 50,000 km. The corresponding times are before, during, and after the Halley flyby and during the approach to Tempel 2. But some measurements should also be made during rendezvous, probably intermittently. Some instruments may have an absorption

mode, using the sun as a source either in a direct view or with a reflector. Needless to say, after the atmosphere has subsided below detectability, such measurements will be at an end and full attention should be given to the nucleus.

SECTION VI

REPORT OF THE SUBGROUP ON DUST AND SOLIDS INVESTIGATIONS

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A. INTRODUCTION

The nucleus is the source of all cometary material. Appropriately, the first goal of the comet mission is to determine the chemical nature and physical structure of the constituents of cometary nuclei. In this mission, a direct way to study the composition of solids making up the nucleus is via collected dust. The nucleus is thought to be composed of two major components which differ substantially in volatility: ices (volatile solids) and dust (non-volatile solids). Ices are thought to be composed of various molecules of which water is probably the least volatile. In this report, we assume that the major components of the ices will be identified through mass spectrometry, remote sensing of the nucleus, and optical spectroscopy of the cometary atmosphere. However, if dust and ice are intimately mixed, as they probably are (see Section B, "Cometary Dust Analogs"), the presence of residual ice in some solid samples must be anticipated. Cometary dust is known to have a silicate component; it may also contain metals, sulfides, oxides, salts, and organic compounds. Some non-volatile solids may be present as boulders too large to be blown off the nucleus.

B. COMETARY DUST ANALOGS

The materials most analogous to cometary dust are two volatile-rich groups of carbonaceous chondrites[1] and interplanetary dust collected in the Earth's stratosphere. The properties of the relevant meteorites are well known, and their elemental compositions form an important basis for this report. However, in what follows, interplanetary dust is discussed in some detail because, although it is similar to chondrites in its chemical and mineralogical compositions, its physical properties are different. Interplanetary dust appears to be the best cometary analog which has been studied on Earth. In fact, it may very well be cometary dust (D. E. Brownlee, in Protostars and Planets, T. Gehrels, Ed; Univ. Arizona Press, Tucson, 1978). However, it should be noted that observations of meteor showers associated with comets show that the strength of cometary meteoroids varies greatly from shower to shower, and there is a real possibility that materials encountered in the environment of a comet such as Tempel 2 may differ substantially from the particles collected in the Earth's atmosphere.

Interplanetary dust collected in the stratosphere is composed of fine-grained, black aggregates which contain approximately chondritic elemental abundances for the 11 most abundant elements in chondritic meteorites. Abundances of C, S, Na and Mn indicate that the particles are at least as volatile-rich as the most primitive meteorites.

Most interplanetary particles are aggregates of roughly equidimensional grains ranging in size from <0.01 to 10 μm. The collected grains are typically about 1 μm in size, but many of these are themselves aggregates of smaller grains. The larger, μm-sized grains are normally single minerals, typically either enstatite ($MgSiO_3$), forsterite (Mg_2SiO_4), or FeS. The submicron grains are mostly ion, magnesium silicates but usually are not enstatite or forsterite. Typically, small grains are not made of the same minerals as the larger grains.

The porosity of the aggregates varies from highly porous, giving particle densities of <1 g cm^{-3}, to quite compact with no open spaces between grains. About 10 percent of the μm-sized particles are single mineral grains and have densities of 3 g cm^{-3} for silicates to 5 g cm^{-3} for iron sulfide. Higher density grains corresponding to metallic iron are exceedingly rare. Grains 0.3 μm in size do not have significant porosity and have densities in the range 2 g cm^{-3} to 5 g cm^{-3}. The fine-grained, porous nature of the aggregates indicates that dust and ice in comets probably will be intimately mixed on all size scales >1 μm. The concept of individual ice grains and dust particles is probably incorrect. Ice will occupy the intergrain pore spaces in the dust particles, and the submicron grains of dust will likely contaminate all cometary ices. Sublimation of ice from the pore spaces in the

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[1] Chemical data on meteorites can be found in the Handbook of Elemental Abundances in Meteorites, B. H. Mason, Ed, Gordon and Breach, N.Y., 1971.

particles will change the density of individual particles with increasing distance from the nucleus. Loss of ice will also tend to fragment the more fragile particles, which may produce changes in the particle size distribution in various regions of the coma.

The aggregate structure of the particles simplifies some collection problems because the particles will tend to crush and fragment during collision with the spacecraft rather than bounce off. But, it is conceivable that when an aggregate particle fragments upon impact, the submicron grains would be retained and the solid, large mineral grains would elastically rebound and be lost. The aggregate structure of the particles also complicates single grain analysis schemes because the submicron components tend to coat the larger grains.

C. SCIENTIFIC OBJECTIVES

In order to understand the cometary nucleus, its constituents and their interactions with the interplanetary medium, a wide variety of data is needed (Table 2-5). Some of these goals can be met only by combining results of a variety of measurements. The Subgroup felt it must define a limited subset of goals which, if met, would permit a reliable, first-order deduction of what are the solid (ices and dust) constituents of the nucleus. These more limited objectives are to determine:

(1) The elemental composition of collected solids (dust and icy particles).

(2) The flux and physical characteristics such as size, shape, velocity, charge, scattering properties, etc., of dust and icy particles.

These data, combined with those derived from other measurements (imaging, remote analysis, mass spectrometry, etc.), will provide the means of addressing most of the goals listed in Table 2-5.

1. Elemental Composition of Collected Solid Particles

The Subgroup concluded that a necessary step to achieving an understanding of the nucleus is to determine the chemical composition of the solids emitted by the comet. Although, ideally, the absolute abundances of all the elements present in cometary material should be determined, this goal is not realistic. By selecting "indicator" elements, each of which is representative of a group of elements in terms of their cosmochemical behavior, measurement of 12-15 elements in the nucleus and dust can yield a rather complete picture of the overall composition of the nucleus. Table 2-6 is a prioritized list of elements selected for this purpose. Instruments for the measurement of elemental composition of the nucleus and the dust should be selected, in large part, on the basis of their ability to measure elements in the first two categories on the list. We note that several instruments

Table 2-5. Science Objectives for Collected Particles[a]

Desired Knowledge	Type of Data Needed
1. Elemental composition	See Table 2-6
2. Mineralogy	Chemistry of individual particles
3. Organic fraction	Abundances of organic molecular fragments
4. Mass flux and size distribution	Measured over large range of sizes as function of cometary activity (0.3 μm - 300 μm)
5. Dust/ice	Density, silicates/(H,C,N)
6. Density	Bulk composition, mass, and volume
7. Light scattering properties	Albedo, polarization
8. Velocities	Over a range of sizes and locations
9. Magnetic and electrical properties	Conductivity, charge

[a]Other important science objectives such as age determination and precise isotopic compositions appear to require return of a sample for laboratory study. A first cometary mission will be highly rewarding without these data.

exist which come reasonably close to achieving this goal (see Section D). A secondary consideration is the amount of dust required for measurement; the smaller the sample required, the more desirable is the instrument.

The instruments should be capable of determining compositions which differ substantially from those expected. The capability of measuring a large number of diverse elements accurately is the best assurance that a reliable determination of the elemental composition of the collected dust will be achieved.

Even in cases in which many elements are measured successfully, we anticipate problems of allocating elements among possible host molecules. The problem is particularly severe in the case of C,

Table 2-6. Measurement Priorities for Bulk Analysis of the Nucleus and Collected Cometary Solids[a]

Rating	Element/Si	ΔR[b]	R in Chondrites
Highest priority	Mg	±0.05	0.7 - 1
	Ni	±0.02	0.04 - 0.1
	S	±0.05	0.1 - 0.7
	H	±0.03	0 - 0.2
Essential (listed in order of decreasing priority)	Fe	±0.2	1 - 2
	C	±0.05	0 - 0.5
	O	±0.3	1.5 - 5
	Na	±0.005	0.03 - 0.06
	Al	±0.01	0.05 - 0.12
	K	$\pm 10^{-3}$	$2\text{-}10 \times 10^{-3}$
	Ca	±0.01	0.06 - 0.14
	Zn	$\pm 10^{-4}$	$1\text{-}30 \times 10^{-4}$
	N	±0.01	$1\text{-}200 \times 10^{-4}$
	Mn	±0.001	0.01 - 0.02
	U	$\pm 5 \times 10^{-8}$	$4\text{-}20 \times 10^{-8}$
	P	±0.001	$4\text{-}20 \times 10^{-3}$
Desirable (Not prioritized, listed in order of increasing atomic number)	Li	$\pm 10^{-6}$	$4\text{-}15 \times 10^{-6}$
	Ne	$\pm 5 \times 10^{-9}$	$0 - 3 \times 10^{-8}$
	Cl	$\pm 10^{-4}$	$4\text{-}600 \times 10^{-5}$
	Ar	$\pm 5 \times 10^{-9}$	$1 - 20 \times 10^{-9}$
	Ti	±0.001	$2\text{-}10 \times 10^{-3}$
	Cr	±0.002	0.02 - 0.03
	Ge	$\pm 10^{-5}$	$6 - 40 \times 10^{-5}$
	Ce	$\pm 2 \times 10^{-6}$	$\sim 6 \times 10^{-6}$
	Xe	$\pm 5 \times 10^{-10}$	$2 - 20 \times 10^{-10}$
	Yb	$\pm 3 \times 10^{-7}$	$\sim 10^{-6}$
	Tl	$\pm 10^{-7}$	$3\text{-}1000 \times 10^{-9}$
	Pb	$\pm 10^{-5}$	$1\text{-}30 \times 10^{-6}$
	Th	$\pm 2 \times 10^{-7}$	$2\text{-}10 \times 10^{-7}$

[a]Weight ratios normalized to Si, R = element (weight fraction)/Si (weight fraction).

[b]The ΔR's are chosen to permit various meteoritic classes to be distinguished from each other and from non-meteoritic material.

Table 2-6. (Cont'd) Notes to Table

Note 1. Accuracies are expressed as $\pm\Delta R$ instead of $\pm\Delta R/R$, because: (a) this is more nearly the way instruments behave; absolute accuracy is independent of concentration, and (b) for those elements that might vary over orders of magnitude in abundance, relative accuracy in the lower abundance range does not usually need to be as great as in the upper abundance range to be informative.

Note 2. The least accuracy (largest error limits) needed to answer a particular question are listed. We attempted to be realistic about what accuracy is really needed to let the instrument developers expend their energies in other directions (i.e., getting more important elements to just barely adequate accuracy instead of a few elements with exquisite precision). The actual error limits are arguable.

Note 3. The five elements (including Si) in the highest priority group contain enough information to test whether the solids are essentially chondritic in composition. In addition, H gives a chance to estimate the dust/ice ratio in the nucleus (since virtually all the ices expected are hydrates).

Note 4. The "essential" group adds the remaining major elements in chondritic meteorites and the remaining most abundant volatile elements (C, O, N). In ice-free dust, these will establish similarity (or dissimilarity) to carbonaceous (or non-carbonaceous) chondrite subgroups.

Note 5. The "desirable" group includes a number of elements that would yield more detailed information on nuclear composition or chemical processes.

S, H, and O which are likely to be present in both ices and dust. Carbon illustrates an extreme case of this problem. In comets, carbon probably occurs in the form of solid CO_2, solid clathrates, and molecules such as HCN. In carbonaceous chondrites, carbon is present in the form of complex hydrocarbons and in carbonate minerals such as calcite. Another set of possible parent compounds arises from predictions that some interstellar grains contain graphite, or carbides such as SiC and TiC. Because of these varied possibilities, allocating carbon to a particular molecule or mineral will require additional information.

A useful addition to the dust analysis that would provide information about host phases is to control the temperature of the collector and to observe the measured composition of solid particles as a function of temperature. Any device or system that would permit volatile elements to be separated between icy and dusty parent components would be helpful. Even more useful would be a means of transferring volatiles outgassed during heating of dust to the inlet of the mass spectrometer, i.e., a crude pyrolysis experiment which would permit identification of organic material.

Elemental analysis of individual grains contributes an additional dimension to the characterization of cometary solids. Analysis of several hundred 1-μm spots on a collected dust sample will identify and determine the relative abundances of various mineral phases which exist as grains larger than 0.5 μm. These data will be very helpful in assessing the nature and possible modes of origin of cometary material. Individual-grain analyses can be directly compared to point-count analyses of meteorites and will provide means for comparing cometary solids with the various meteorite types.

Previously noted problems will be reduced to some extent if a large data set is compiled. Furthermore, many details regarding cometary behavior may emerge from the analysis of a variety of samples, particularly, if there are heterogeneities in the cometary environment. We suggest that on the order of 100 dust samples should be collected and analyzed. Note that several samples may be collected simultaneously. However, because a comet is a dynamic object, the Subgroup regards the ability to make repeated measurements over a long period of time as highly desirable.

2. Flux and Physical Characteristics of Solid Particles

The flux and physical characteristics of solid particles in the vicinity of the nucleus are of scientific interest as well as being important to the safety of the spacecraft. Size frequency distributions and shape data on interplanetary dust, meteoroids, and meteorites are available from a wide variety of experiments. Attribution of some or all of these materials to a cometary source requires obtaining comparable data for solids in the cometary environment. The Subgroup recommends that the flux of large dust particles be monitored as part of the spacecraft hazards protection system (in addition to measurements made by science instruments which will probably concentrate on smaller sizes), and that the information obtained be made available for scientific study. Close coordination between the efforts of the spacecraft designers and the dust experimenters in this area is recommended.

D. INSTRUMENTS

Instruments are discussed in terms of the relevant scientific objectives, i.e., (1) to determine the elemental composition, and (2) to determine the flux and physical characteristics of dust particles.

1. Elemental Composition of Collected Solids: An Example of a Possible Experiment

The capabilities of some existing or proposed instruments for measuring elemental composition are summarized in Table 2-7.

As discussed previously, achievement of the scientific objectives requires analysis of 12 to 15 elements, including the constituents of ices and organic compounds in both bulk samples and individual particles. To do this, the collected dust analyzer is envisioned as a package of two to four different analysis instruments which share, to varying degrees, a dust collection and distribution facility, a detector cryogenic cooling unit, and electronics for power conditioning, data handling, engineering measurements, and command sequencing. The science instrument subassemblies in this instrument package might include:

(1) A particle analyzer (e.g., miniprobe or laser mass spectrometer).

(2) A bulk composition analyzer (e.g., CAPX = alpha backscatter, XRF = x-ray fluorescence, or SIMS = secondary ion mass spectrometer).

(3) An organics analyzer (e.g., PyMS = pyrolysis mass spectrometer or SIMS).

The estimated mass, power consumption, and acceptable environmental temperatures are given in Table 2-8. Power levels given in parentheses represent short, peak-power requirements.

The capabilities of some of these instruments are given in Table 2-7. It is clear that the goals set forth by the Subgroup are within reach of either single instruments listed or of appropriate combinations of these instruments.

For planning purposes, this experiment can be considered to have a rectangular envelope some 1.0 x 0.65 x 0.3 m with some small protrusions (Miniprobe, SIMS, and funnel concentrators). During dust collection, the collecting disk axis should be pointed to within ±20 deg of the direction of the incoming dust. Far from the nucleus, this direction may be taken to be the direction of the spacecraft's motion if the relative motion of the spacecraft exceeds that of the dust. Near the comet, the dust comes from the nucleus. When funnel concentrators are being used, especially in the initial stage of rendezvous, the alignment requirement is more critical: probably ±8 deg. Peak data generation will be 1 Mb/day. The experiment central electronics will be capable of storing individual sample analyses, but will require periodic readout of memory to the onboard data storage subsystem. This data transfer will contain a maximum of 80 kb and occur no more often than at 100-s intervals. The particle and bulk analyzer are expected to acquire about 1000 individual spectra during the first 3 months of rendezvous, equivalent to an <u>average</u> data rate of less than 10 b/s. Periodic updating of

Table 2-7. Examples of Instrument Capabilities: Detection of Elements in Table 2-6

	Collected Solids Analysis Method[a]			
Element	CAPX	Miniprobe	SIMS	XRF
Si	X	X	X	X
Mg	X	X	X	X
Ni	X	X	X	X
S	X	X	X	X
H	X		X	
Fe	X	X	X	X
C	X	X	X	X
O	X	X	X	X
Na	X	X	X	X
Al	X	X		X
K	X	X	X	X
Ca	X	X	X	X
Zn		X		X
N	X			
Mn		X		X
U				
P		X		X
Detection limits	Specified in Table 2-6 except K	0.2 wt% for most elements 2% for C ∿1% for Na	ppm, not quantitative for elemental abundances	Specified in Table 2-6

[a]CAPX = alpha backscatter and excitation, α, p and X-ray modes.
Miniprobe = electron beam/energy dispersive X-ray detector.
SIMS = secondary ion mass spectrometer.
XRF = x-ray fluorescence and detection.

commandable sequences will be required on roughly a weekly basis. The command load for the collection and individual analyses will total approximately 3 kb per uplink.

2. Flux and Physical Characteristics of Solid Particles

Two examples of instruments which have been flown previously and might be modified are the Pioneer Venus particle size spectrometer and

Table 2-8. Engineering Characteristics of Collected Dust Instruments[a]

Instrument	Mass, kg	Power, W	Temperature Range, °C	
			Rendezvous	Cruise
Dust collector	4	(25)	-50 to 100	-50 to 125
Particle analyzer	8	5	0 to 60	-25 to 100
Bulk analyzer	3	2	0 to 60	-25 to 100
Organic analyzer	8	(50)	0 to 60	-25 to 100
Central electronics	4	10	0 to 80	-25 to 100
Thermal control	6	(0)	NA	NA
Total	33			

[a]This is an example of a dust collector and analyzer package. Various substitutions or omissions are possible.

the Apollo LEAM experiment. However, new instrumentation based on the principle of light scattering is also under development for real-time measurement of particle flux, velocity, and particle size distribution. Another promising device, which has not been flown before, is the tapered element oscillating microbalance, a sensitive mass measurement device suitable for particulate and vapor deposition or sublimation measurements. The microbalance measures cumulative mass and size distributions. The Subgroup recommends that emphasis be placed on instruments capable of making measurements over a wide range of masses.

3. Halley Flyby

At Halley, the main goal is to measure the flux, mass distribution and gross composition of the ambient dust. Although this fast flyby requires different techniques of dust analysis from those applicable to the Tempel-2 rendezvous, suitable instruments can be designed. For example, a dust impact analyzer, which measures composition by time-of-flight mass spectrometry of the ions generated by impacts, has been flown successfully on Helios 1 and 2. Such an instrument, properly modified, should be suitable for the Halley flyby.

E. GENERAL REMARKS

The Subgroup identified two areas in which more developmental effort is needed.

(1) Cooling systems for solid-state x-ray and γ-ray detectors.

(2) Dust collection systems.

With regard to cooling systems, we endorse the efforts funded by NASA to develop x-ray detectors which can operate at "room" temperature. Nevertheless, as such detectors are still under development and as other instruments[4] also have cooling requirements, a central cooling system might prove practical and the possibility should be investigated.

Dust analysis experiments require, first of all, that the dust be collected. Dust collection techniques are being investigated by individual investigators interested in developing dust analysis experiments. Nevertheless, there are two common technological problems shared by most instruments:

(1) Substrates with a high collection efficiency are needed. It is known that viscid (sticky or tacky) organic materials will collect dust with high efficiency. Such substrates should be tested to see if they will retain these characteristics after long periods in space. In addition, substrates which do not contain C,H, and O, which comprise the organic substrates, should be identified and tested. In order to achieve the scientific goals and accommodate the requirements of various dust analysis experiments, substrates of several different compositions or types may have to be flown. Their characteristics must be thoroughly tested as soon as possible.

(2) The methods of varying the temperature of the dust collecting substrate should be investigated and tested.

F. MISSION STRATEGY (RENDEZVOUS ONLY)

Dust collection should begin as early in the mission as possible and should continue throughout the mission. This means the dust collector must be located in a position on the spacecraft where collection will be possible at all times. Dust collection should certainly be attempted during mission Phase I, as far as 10^4 km from the nucleus. The miniprobe will return useful data as soon as roughly 10^3 particles (larger than 4 μm in diameter) per square centimeter are collected.

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[4]The gamma-ray detector, the imaging system's charge-coupled devices, mass spectrometer walls, infrared detector, dust collection substrate, etc.

During this initial phase, most data will be from this device, although the bulk analyzer will also periodically monitor its targets. Post-perihelion collection passes should be made to collect several bulk samples which are large enough ($\sim 100\ \mu g/cm^2$) to permit high accuracy analyses. Emphasis will then shift to bulk analysis. As the range decreases during subsequent phases of the mission, and the flux increases, it will become possible to do "snapshot" sampling for study of heterogeneities in the nuclear surface and temporal variations in the rate of dust emission. If such variations are detected, they will be used to aid the particle analyzer in planning "snapshot" samples of its own. In addition, large and small particle filters and magnetic brooms may be employed to attempt concentration of selected types of dust. After several months of rendezvous, the data acquisition rate of the analyzers may decrease significantly.

The Subgroup is concerned that the post-perihelion mission strategy be well defined and that adequate time in this phase be set aside for dust collection and analysis during the close approach to the nucleus. Implementation of an adaptive strategy leading to close approach to the nucleus takes time. Past observations suggest that the activity of Tempel 2 will have subsided adequately to permit an arbitrarily close approach to the nucleus within a year of rendezvous. In addition, many of the science objectives outlined earlier require that data be collected over a significant portion of a comet's orbital cycle. The Subgroup strongly endorses the 1-year, post-rendezvous mission profile.

G. SUMMARY OF RECOMMENDATIONS

The recommendations of the Dust and Solids Subgroup can be summarized as follows.

1. Instrumentation

(a) Instruments capable of analyzing 12-15 elements including volatiles in both bulk collected dust and individual particles must be part of the science payload.

(b) An instrument capable of measuring fluxes and physical characteristics of dust, such as sizes, shapes, velocities, charge, etc., should be part of the science payload.

(c) Dust collection methods are being developed and tested. Thorough testing must continue until a variety of substrates have been characterized. The temperature of the collector substrates is important and should be controllable.

(d) If practical, volatiles outgassed by heating collected dust should be identified and analyzed.

(e) The dust collector must be located on the spacecraft so that it faces the comet and minimizes spacecraft structural obscuration within a 45-deg conical field of view.

2. Spacecraft

(a) Monitoring of dust flux should be a spacecraft function, and should include the capability of detecting particles greater than 1 mm in radius.

(b) The possibility of a central cooling facility serving a variety of instruments such as γ-ray and x-ray detectors, imaging (CCDs), near-infrared detectors, mass spectrometers, and dust collector should be investigated.

(c) The spacecraft should be able to withstand the dust environment necessary for dust collection, i.e., at least six collection passes intercepting integrated dust fluxes of 100 $\mu g/cm^2$ each.

3. Mission Strategy

(a) The mission should last for at least 1 year following rendezvous.

(b) Initial dust collection should take place during Phase I of mission rendezvous operations and continue throughout the mission. On the order of 100 dust samples should be collected over the duration of the post-rendezvous mission. It is expected that several samples can be collected simultaneously using different substrates.

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SECTION VII

REPORT OF THE SUBGROUP ON REMOTE SENSING OF THE NUCLEUS

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A. INTRODUCTION

The primary objective of a first comet mission is to characterize the physical and chemical nature of cometary nuclei. Two basic approaches are possible for a rendezvous mission. The first is by analysis of materials, gas and dust, released from the nucleus, as heating by sunlight causes volatiles (together with entrained solids) to evolve from its surface. The second is by remote sensing; that is, by the measurement of radiation reflected from or emitted by the nucleus. This report discusses the role of remote sensing as a tool for accomplishing these primary mission goals.

One important remote sensing tool is multi-spectral imaging, which is capable of studying a wide variety of morphological, photometric, and colorimetric properties of the nucleus at high spatial resolution. Because of its crucial role in any suite of remote sensing instruments, the imaging system is considered in detail in a separate Subgroup Report (Section IV). Here we assume the presence of a high-resolution, multi-spectral imaging capability as an essential complement to the other remote sensing instruments described below.

We also note at the outset of this report that the nucleus is probably heterogeneous, with regions of differing composition and physical characteristics. The remote sensing tools should be able to resolve small areas of the nucleus.

To accomplish the remote sensing goals of this mission, we require the capability of a rendezvous spacecraft to operate for tens of days within a few hundred kilometers of the nucleus, and some instruments require periods of a month at distances less than 10 km. The instruments described here will, unfortunately, be of limited use during the fast flyby of comet Halley at a range of some 10^5 km from the nucleus.

B. OBJECTIVES

Specific objectives of remote sensing investigations concerning the nucleus are:

(1) To determine the elemental composition of the nucleus.

(2) To measure surface temperatures and determine the energy balance in order to investigate the physical structure of the surface material and the nature of the evaporating volatiles.

(3) To determine the mineralogic composition of the surface materials.

C. MEASUREMENTS AND TECHNIQUES

The three major objectives listed above can best be addressed by the following types of measurements:

(1) x-ray and γ-ray spectroscopy.

(2) Radiometry.

(3) Spectral measurement of reflected sunlight.

All of these techniques have the capability of mapping units of differing physical and chemical properties on the surface of the nucleus. Thus, these investigations complement the <u>in situ</u> analyses of gas and dust, which yield information on the nature of material making up the nucleus, but not its distribution. The remote sensing instruments form the vital bridge required to relate the material in the cometary atmosphere to the processes releasing that material from the body of the nucleus itself, and hence to the evolutionary history of the comet.

1. Measurement of Elemental Composition

The elemental composition of the cometary nucleus is key information for understanding the formation of comets. Abundances of non-icy elements provide links to the different classes of meteorites. Ratios of H (or possibly O) to non-volatile elements such as Si provide estimates of the ice-to-rock ratio in the surficial layer. Although

important information regarding non-volatile solids will be obtained from the analysis of collected dust (see Section VI), the existence of these data does not supplant the need for direct study of the nucleus.

Because of uncertainties regarding the ratio of silicates to more volatile constituents, it is useful to discuss the analytical requirements as ratios relative to Si, which is neither volatile nor refractory during nebular condensation. In a remote sensing experiment, it is important to determine the fractionation of materials by measuring representative elements that are refractory (e.g., Mg, Al), volatile (e.g., S, H), and siderophile (e.g., Fe). In Table 2-6, the ranges (R) in the ratios of a number of elements to Si are indicated for various meteorite classes, together with the precision (ΔR) required to distinguish significantly different meteorite classes. The conclusions presented in Section VI with respect to analysis of the collected dust apply also to remote sensing of the entire nucleus.

The measurement of elemental abundances in the nucleus could be addressed by either x-ray spectroscopy or γ-ray spectroscopy. Early generations of both instruments were flown in the Apollo mission. Engineering details of more recent versions have been published; additional information has been provided by some of the developers. The discussion that follows is made in the context of Table 2-6.

An x-ray experiment can be designed to measure all major elements from C to S, and possibly those from Ca to Ni as well. Detection is strongly dependent on solar activity. The abundant elements Mg, Si, S, C, O and Al (and Na, K and Ca if their concentrations are high) can be measured with sufficient accuracy. The x-ray experiment measures composition to a depth of a fraction of a millimeter, and is capable of moderate areal resolution.

The gamma-ray experiment measures all major elements (with the possible exception of Ca) and the radioactive elements, U and Th. The major elements include H, C, O, Mg, Al, Si, S, K, Fe, and Ni; Na can be measured if its concentration is high. The depth of measurement is tens of centimeters. Areal resolution is limited to spatial scales comparable to the distance from the nucleus.

Both types of instruments require long stay times in close proximity to the nucleus in order to achieve their potential in areal resolution and precision of measurement. Focusing optics can be used to allow an x-ray system to achieve resolution up to perhaps 0.1 rad, but the γ-ray system can resolve only areas on the order of 1 rad in extent; thus, the closer the orbit, the better regions of heterogeneous elemental composition can be distinguished. These data will be best obtained late in the mission, after the rendezvous spacecraft has gone into orbit around the nucleus of Tempel 2.

The instrumentation for both the x-ray and γ-ray spectroscopy is developed, and only moderate modifications are required from designs already proven in space during the Apollo flights.

2. Measurements of Temperatures and Radiative Balance

The three primary scientific goals of radiometric measurements of the nucleus are:

(a) To determine the sublimation temperature of volatiles, and the distribution of temperature in regions of differing composition or morphology.

(b) To determine the thermophysical properties of the surface material at a variety of locations.

(c) To determine the local energy balance of different surface regions during periods of significant activity.

All of these goals are of equal priority; they are listed in order of increasing difficulty based on current instrument concepts.

Goal (a) can be accomplished in a straightforward way by measuring the surface temperature at many points over the nucleus. This temperature is an important indicator of the nature of the volatiles; similar data from Mariner 7 were used to show that the martian seasonal polar caps were CO_2. It is expected that the surface temperature on a comet during active phases will depart significantly (by tens of degrees) from that of a body in thermal equilibrium with the insolation.

Goal (b) can be accomplished by mapping the surface temperature, particularly on the unilluminated side, at a period when the comet is relatively inactive. The rates of cooling and heating yield values of the thermal inertia, which is primarily sensitive to the degree of consolidation of the surface material. Variations of thermal inertia are expected for regions of differing composition and morphology. The possible presence of a wide size distribution of surface particles, particularly both a dusty and a "blocky" (>10 cm in diameter) residue, could be investigated by looking for a non-blackbody signature of an anisothermal surface using several infrared passbands.

Goal (c) requires measurement of both thermal emission and the energy input from absorbed insolation. It is also necessary to determine the internal energy budget; that is, the amount of heat conducted to and from the interior. If these processes are properly accounted for, one can derive the amount of energy being used for evaporation of volatiles. This value then yields the product of heat of vaporization and vaporization rate; in conjunction with the mass spectrometer data, both of these important factors can be evaluated to provide basic data on the sublimation rate of the comet and the physical-chemical state of its volatiles.

Two basic types of instruments can accomplish these goals: a multi-channel infrared radiometer or a multi-channel millimeter-wave radiometer. Because they operate in different regions of the spectrum, these two instruments are sensitive to thermal radiation from different depths below the surface and are affected in different ways by the primary expected sources of uncertainty in measuring temperatures.

The infrared radiometer, which would probably cover several broadband spectral intervals in the wavelength range from 10 to 60 μm, measures thermal radiation arising at or very near the surface. Since the wavelength region sampled is that in which the majority of the thermal radiation from the comet is emitted, the measurements yield a model-independent effective temperature, and the data can be used directly to determine the energy balance. The spatial resolution of infrared radiometers is high (up to 0.1 milliradian), and because the measurements are made in spectral regions where emitted flux is proportional to a high power of the surface temperature, the precision in temperature measurement is very high (a fraction of a degree). In addition, the use of several passbands spanning the blackbody peak allows the partial separation of components of different temperatures even when they are not spatially resolved. One potential problem is the possible interference from dust. Comets are surrounded by dust clouds which have temperatures much higher than those expected for the nucleus itself, and even a fraction of an optical depth of such dust could mask the signal from the nucleus. Techniques that utilize the differing spectral and spatial properties of dust emission and nucleus emission must be developed to make useful measurements of the nucleus. These problems apply only to the active phases of a comet; goal (b) can be accomplished in a straightforward way when the activity has declined and the dust cloud has dissipated.

The millimeter radiometer has the great advantage, as far as measuring the properties of the nucleus is concerned, that it cannot see the dust envelope since the dust is a very inefficient radiator of millimeter wavelengths. Furthermore, as the radiation detected at different wavelengths arises at different depths, multi-wavelength measurements can be analyzed in terms of a model to yield the thermal and electrical properties of the surface. It would be desirable to make measurements in several millimeter-wave bands; these would probably probe effective depths of a few millimeters to a few centimeters depending on the microwave opacity of the surface. As these measurements are made at the tail end of the thermal emission spectrum, the effective temperature is not measured directly, but can be inferred. The spatial resolution of the millimeter radiometer is expected to be an order of magnitude coarser than that of the infrared instrument. The precision of the temperature measurements will also be lower.

In addition to the thermal measurements, a determination of energy balance requires that the insolation and the Bond albedo be measured. A broad-band visible radiometric detector should be included to measure accurately the total incident and reflected sunlight. These measurements must be made at a variety of geometries to establish the photometric phase function of the surface. It seems reasonable to expect that an accuracy of 5 to 10 percent could be achieved in determining absorbed energy. These values, together with the measurements of thermal emission, will establish the fraction of insolation going into volatilization of nuclear material if 10 percent or more of the incident energy is so used.

Infrared radiometers have been successfully flown on many space missions, including Mariners 2, 6, 7, 9, and 10; Apollo; Pioneers 10 and 11; and Viking. Only minor changes will be required for a comet mission. Millimeter-wave radiometers have not been flown, but designs exist and development work is continuing.

3. Reflectance Spectrometry: Ultraviolet, Visible, and Infrared

Reflectance spectrometry is the technique best able to determine the mineralogy of the surface, including identification of both ices and silicate minerals. The primary goals of such measurements are:

(a) To identify the mineral phases of ices, silicates, oxides, sulfides, carbonates, and other materials on the surface of the nucleus.

(b) To study the spatial distribution of these mineral phases as a means of exploring the heterogeneity of the nucleus and investigating its evolution.

Reasonably high spatial resolutions (on the order of 0.1 milliradian) can be achieved, so that it should be possible with a mapping spectrometer to investigate mineralogic heterogeneity at a scale of a few meters on the surface.

Three spectral regions are usually considered in reflectance spectrometry: ultraviolet, visible, and infrared (to about 5 μm). Each will be considered in turn.

In the vacuum ultraviolet, the energy of a photon is on the same order as the valence-conduction band gap in many solids of geologic interest. This region has only recently been explored for remote sensing of solids, particularly of rough or powdered samples such as are expected on the surface of a comet. The transitions producing spectral features are largely those involving inner-shell electrons, and they are generally diagnostic of minerals different from those frequently encountered in infrared spectrometry. Recent laboratory measurements of powdered lunar samples at spectral resolving powers of about 100 clearly show spectral features due to olivine, ilmenite, Ca-feldspar, augite, and other minerals. However, since this remains at present a new and relatively unproved technique for remote sensing of planetary bodies, we expect that an ultraviolet spectrometer will not be the primary device for cometary reflection spectrometry. The best solution would be to include a UV capability in an infrared spectrometer, or to combine the functions of both gas and solid UV spectrometry in a single instrument. (The use of UV spectrometry for remote sensing of the cometary atmosphere is discussed in Section V.)

In the visible part of the spectrum, additional diagnostic electronic transitions take place, particularly band edges in the blue and near ultraviolet. It may be possible to obtain the derived spectral information, however, from the multispectral imaging system, especially if a CCD with extended near-UV response is used as a detector.

The spectral region that has been primarily utilized for mineralogic remote sensing of solar-system bodies is the infrared, including wavelengths from about 0.7 to 5.0 μm. Both molecular and electronic absorption bands appear in the infrared reflectance spectra of many solids. Especially diagnostic are features due to ices (H_2O, NH_3, CH_4, etc.) and such silicate minerals as olivine, oxides of iron, plagioclase, pyrozene, and salts. The exact wavelength positions of the absorption band centers depend upon the types of ions present and on the dimensions and symmetry of the sites in which the ions are situated. The presence of many mineral phases are readily identified, but quantitative abundances are less secure, requiring assumptions about relative grain sizes and degree of homogeneity within the instrument field of view.

A typical infrared spectrometer for remote sensing of the surface should cover the wavelength interval from about 5.0 μm down to at least 0.7 μm, with a further extension toward short wavelengths desirable. A resolving power of 100 is adequate to identify the anticipated spectral features. In addition, it is highly desirable to include an imaging capability, at least in one dimension, to map the distribution of mineralogic components over the nucleus and to provide compositional information to be compared with high-resolution imaging data.

Optical spectrometers of varying types have flown on numerous spacecraft. Ultraviolet spectrometers not substantially different from those useful for a comet mission were included in the payloads of Mariners 6 and 7, Mariner 10, and Voyager, and are under development for Galileo and Earth orbital applications. A near-infrared spectrometer with spatial mapping characteristics was selected for Lunar Polar Orbiter and is under development for Galileo. Both ultraviolet and infrared instruments should be readily adaptable to the requirements of a comet mission.

D. MISSION STRATEGY

Remote sensing of the nucleus places the following constraints on strategy for the rendezvous mission:

(1) The spatial resolution of all remote sensing instruments is inversely proportional to their distance from the nucleus. In general, they will achieve significant spatial resolution only at distances of less than 100 km.

(2) The radiometer can achieve its objectives only if it is possible to observe the unilluminated hemisphere of the nucleus from ranges of 100 km or less at some time during the mission.

(3) The elemental composition can be determined only from ranges of less than 100 km, and significant spatial resolution can be achieved only at ranges less than 10 km. To achieve its stated objectives, such an investigation requires that the spacecraft orbit the nucleus for at least 30 days at a distance under 10 km.

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SECTION VIII

REPORT OF THE MASS DETERMINATION, RADAR, AND RADIO SCIENCE SUBGROUP

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A. INTRODUCTION

The scope of this Subgroup's concern is more loosely defined than the others. It arises from an approximate convergence of the scientific usefulness of radio and radar techniques and certain of the scientific objectives of the rendezvous mission, particularly those concerned with the mass, density, homogeneity, and internal structure of the nucleus.

It is not expected that any of these techniques will be applicable during the fast flyby of Halley.

B. OBJECTIVES

Scientific objectives at Tempel 2 in the areas covered by this Subgroup are:

(1) To measure the density of the nucleus of Tempel 2 to 10 percent or better. This will require reliable measurement of both the mass and the volume of the nucleus.

(2) To characterize small-scale roughness and structure of the surface of the nucleus.

(3) To detect and measure deviations of the gravitational field of the nucleus from spherical symmetry, and thereby obtain data on the degree to which the internal mass distribution is homogeneous.

(4) To investigate the internal structure of the nucleus by using radio-sounding techniques.

C. INSTRUMENTS AND MEASUREMENTS

1. Mass Determination

A prime scientific objective of this mission is to determine the mass of comet Tempel 2. The following data types will be used in the mass determination:

(1) The spacecraft-to-comet range from radar altimeter data.

(2) The apparent size and shape of the nucleus and its position against the stellar background as seen by the imaging cameras.

(3) Earth-to-spacecraft doppler and range measurements.

(4) The apparent location of the comet against the stellar background as seen from Earth.

(5) Spacecraft accelerometer measurements to determine accelerations other than those caused by the gravity field of the nucleus, e.g., cometary dust and drag effects and solar radiation pressure.

The radar altimeter will also be used for near-comet navigation and to provide spacecraft-comet distance determinations for other science instruments (e.g., imaging, x- and γ-ray spectrometers). Hence, the radar altimeter measurements will not only support the mass determination experiment, but will assist in the determination of the nucleus' size, shape, volume, mean density, and roughness.

Preliminary calculations indicate that a 10-percent mass determination could be achieved with a single low-velocity (1-m/s) flyby of a 1.5-km radius comet at a distance of 100 km. It seems probable that the accuracy of this measurement could be significantly improved by more extensive measurements at closer distances and by optimal combination of ground-based doppler and range measurements, on-board radar, and imaging data. Further work is in progress to evaluate quantitatively the possible extent of this improvement and its implications regarding mission strategy and navigation requirements.

a. <u>On-Board Instruments Required for Mass Determination.</u>

(1) Radar Altimeter.

(a) Modifications to existing altimeters are required to vary pulse type.

(b) Required modifications depend only upon the application of existing techniques and should be completed in the available time. The instrument should have an approximately 25-m range resolution at 200 km and a velocity accuracy of <1 m/s.

(2) Accelerometer.

(a) The accelerometer must have a range to cover the maximum thrust acceleration of the ion drive engines ($\sim 2 \times 10^{-4}$ m/s^2) and the nongravitational accelerations affecting the spacecraft ($\sim 10^{-8}$ to 10^{-9} m/s^2).

(b) A three-axis accelerometer that meets these requirements has been flight-tested.

b. Spacecraft Requirements.

(1) The radar altimeter requires a parabolic antenna with $\sim$1 m diameter and with articulation capability. The power and data rate requirements would be about 25 W and 0.2 kb/s.

(2) The accelerometer should be located at the center of mass of the spacecraft and be capable of in-flight calibration.

c. Mission Operations. Mass measurements should be made from a close orbit of the nucleus or during a series of very slow, close flybys. Ideally, these flybys should be made under the following circumstances.

(1) Large heliocentric distances, $\geq$1.8 AU.

(2) Small spacecraft-comet ranges; $\leq$10 km is required for a $\leq$5% mass determination.

(3) Flybys should be on the night side of the nucleus.

(4) The solar panels should be edge on to both the cometary gas and dust flows and solar radiation.

(5) The spacecraft orbital plane should be at right angles to the plane of the sky as seen from Earth.

(6) If it appears possible to investigate a comet's gravity field using ground-based radio tracking of an orbiting spacecraft together with spacecraft-comet ranging, then several different types of orbits about the nucleus would be desirable. Spacecraft orbits of varying orientations and distances from the nucleus might allow separation of different harmonics of the gravity field of the nucleus.

d. Questions Currently Under Investigation.

(1) For a given desired mass determination error, what accuracy is required of the radar altimeter and accelerometer? For a given desired error, what post-rendezvous strategies are required for optimum mass determination measurements?

(2) What mass determination errors can be expected using:

(a) Only altimeter and accelerometer data?

(b) Only ground-based doppler and on-board accelerometer data?

(c) On-board measurements from altimeter, accelerometer and optical imaging and ground-based measurements of spacecraft doppler and range?

(3) What are advantages and disadvantages of including a gravity gradiometer in the rendezvous science payload? Can a gradiometer, in a close nucleus orbit, given information on the comet's mass distribution and internal structure?

2. Density

The density of the comet nucleus places more constraints on its composition and structure than does the absolute value of the mass, discussed above. Determination of the density requires measurement of the volume with an accuracy comparable to the mass determination. The volume measurement can be made by mapping the shape of the nucleus using the imaging system, the length scale being provided by the radar altimeter data.

The principal constraint imposed on the imaging strategy is the requirement of completeness of coverage. On the basis of ground-based studies of non-gravitational accelerations, Sekanina has estimated that the spin axis of Tempel 2 lies almost in the plane of its orbit. To obtain complete sun-lit mapping of the nucleus, it is therefore likely that an extended time (3 to 6 months) will be required to determine the volume, and that pictures will be required both before and after perihelion. The ultimate accuracy achievable is difficult to estimate quantitatively in view of uncertainties regarding the extent and permanence of surface features needed to facilitate mapping, the possibility of a highly irregular surface, and possible problems with obscuration of the surface during a portion of the mission. Provided that these problems are not too serious, it is estimated that the volume can be measured to 2 or 3 percent by taking about 100 narrow-angle pictures of the nucleus and about 100 wide-angle pictures of the nucleus against the star background from a distance of about 1000 km.

3. Surface Structure of the Nucleus

The radar altimeter could also provide information on the morphology of the surface of Tempel 2. Short-pulse radar echoes from a rough cometary surface would be dispersed in time in a way that depends primarily on the large-scale surface geometry and the small-scale surface roughness. The total energy in the echo is controlled by the geometry, the small-scale surface roughness, the surface material, and

the radar parameters. As the large-scale geometry would be well known from a combination of images and the radar range measurements, this factor could be removed from the data.

For surfaces of small or moderate roughness (rms slope $<\sim 0.2$), the effects of roughness and the surface material are separable, and can be quantitatively expressed as rms slope, on horizontal scales of 10 to 100 wavelengths (centimeters to meters for the altimeter), and surface reflectivity. For silicate materials, reflectivity is strongly determined by density and is nearly independent of composition; for ices, the relationships are not well known, but could be obtained by laboratory measurements.

A rougher surface (rms slope $> \sim 0.2$) would result in increased dispersion of the echo in time and significant coupling between the effects of the surface material and the roughness. These parameters would not be separable in scatter from a very rough surface, although the effects of increased roughness would be readily apparent. Alternatively, highly dispersed scatter could also be indicative of a translucent surface, e.g., a terrestrial snowbank, in which multiple scatter is important. Examples of both low- and high-dispersion surfaces are found in radar studies of the terrestrial planets (low dispersion) and the Galilean satellites (high dispersion).

A priori, a cometary nucleus could possess a wide range of surface morphologies. Sublimation of a pure ice could leave a very smooth surface condition, while outgassing of a rock/ice matrix might plausibly leave a much more complex structure. Radar scatter provides a method to probe surface structure on horizontal scales that are smaller than suggested for imaging systems. As a minimum, a map of relative roughness could be obtained for comparison with features observed in images. Quantitative information related to surface roughness and electrical permittivity could also be obtained provided that the surface is sufficiently well behaved.

4. Deviation of Gravitational Field from Sphericity

In accordance with the prime objective of characterizing the nucleus, any measurements which can provide information regarding its internal structure requires serious investigation. A non-spherical distribution of mass in the nucleus will cause its gravitational field to deviate from that of a simple inverse square law. At least in principle, these deviations can be measured by a spacecraft in the vicinity of the nucleus. These deviations could be associated with a non-spherical shape of the nucleus, or by inhomogeneity of its internal mass distribution. The combination of imaging data and gravity measurements could thus provide information concerning the uniformity of the internal structure which, although not uniquely interpretable, could provide significant constraints on models of the nucleus.

The gravitational field can be measured either by its effect on the motion of the spacecraft or by onboard instrumentation, e.g., a gravity gradiometer. The ongoing study described in Section VIII-C-1 (Mass Determination) is also concerned with the extent to which it is feasible to detect and measure deviations of the gravitational field from spherical symmetry. Quantitative statements on this matter must await the outcome of this study. However, it is very likely that such measurements will at least require extended operation in the vicinity (i.e., ~ 10 km) of the nucleus.

5. Internal Structure of the Nucleus

Any information on the internal structure of a comet nucleus would provide clues to the processes operating at the time of the formation of these bodies. Specific objectives are:

(a) To determine if the nucleus has a rocky core.

(b) To determine the size of the core.

(c) To determine the thickness of a possible icy crust and the presence of layers.

(d) If the nucleus has only icy patches, to determine their depth and total volume.

The internal structure of the Tempel 2 nucleus can be studied remotely using an active radio sounder experiment. One concept of such an experiment uses a dual-frequency pulsed sensor (Table 2-9). One mode is a low-frequency (60 MHz) mode which has high penetration, low range resolution capability. In the other mode, at 180 MHz, the penetration is lower and the range resolution is greater. A similar sounder has been used over the last few years to sound polar ice sheets (Greenland, Antarctica) down to depths of many kilometers.

One group will have completed a proof-of-concept sensor for a comet mission by the end of summer 1979. With such a sensor, a 1.5-km-radius nucleus can be detected from a range of 360 km. Near surface sounding (depths of 100 to 200 m) can be done from a range of 100 km for most icy materials. Deep sounding (more than a few hundred meters) requires a much closer range, preferably less than 10 km.

The possibility also exists of combining the radar altimeter and the radio sounder. The present altimetry requirements for engineering and navigation purposes are:

(a) Detection range: ≥1000 km.

(b) Range accuracy: ≤25 m.

(c) Turn around data processing time: near-real time for automatic navigation.

Table 2-9. Comet Nucleus Sounder: Possible System Parameters

Parameter	Mode 1	Mode 2
Frequency, MHz	60	180
Wavelength (in vacuum), m	5	1.66
Pulse length, μs	5	1.5
Bandwidth, MHz	6	20
Signal modulation	Chirp	Chirp
Range resolution, m		
In free space	25	7.5
In ice (ε = 3.4)	15	4
Pulse return factor, Hz	100	100
Peak power transmitted, W	500	500
Average power transmitted, W	0.25	0.07
Antenna gain, dB	6	6
Antenna field of view, deg	±30	±30
Receiver noise, K	600	600

Mass, kg: 10 to 12.5, including antenna.
Power, W: 20 to 25.
Size, cm: 30 x 30 x 10.

The sounder can easily meet the range accuracy requirement. It possibly can meet the near-real-time requirement of range data for automatic navigation. The main problem would be to develop an algorithm that would minimize the confusion between surface and subsurface echoes. The main limitation of the sounder is the detection range requirement. Realistically, the maximum detection range of a reasonable sounder is about 400 km.

Thus, if the detection range requirement can be relaxed by a factor of 3 or more, it is conceivable that the sounder can be used as an altimeter.

D. POSSIBLE RADIO OCCULTATION BY THE COMA

This measurement could, in principle, determine the integrated columnar plasma content along the radio path from the spacecraft to the Earth by using the communications radio of the spacecraft. There are three requirements that must be met if useful information is to be obtained.

(1) The trajectory must be such that the spacecraft is occulted by the coma. This favorable geometry does not occur during the Halley flyby as presently planned.

(2) The occultation must also be planned to occur within a characteristic period of <1 hour if the effects of the cometary plasma are to be separated from those of the solar wind and the Earth's ionosphere. This excludes the rendezvous phase of the Tempel 2 mission.

(3) The plasma density must be sufficiently high. Models of Ip and Mendis and Giguere and Huebner indicate densities of N(100 km) $\approx 10^{11 \pm 1}$ cm^{-2} for active, 1-km radius comets near 1 AU. This would permit signal-to-noise ratios of 10:1 to 30:1 for such an active comet. Tempel 2 might be expected to be about two orders of magnitude less active; thus, detection of an effect would be marginal, even considering possibly more favorable geometry.

It is also conceivable that, during the rendezvous phase at Tempel 2, maintenance of a relatively fixed geometry with the radio path passing near the nucleus would permit detection of transient changes in columnar content. Such measurements would be very difficult and would require careful attention to mission and spacecraft design.

E. STRATEGY

The major objectives outlined above place the following constraints on the mission strategy.

(1) Minimally accurate mass data will require at least a single slow flyby (1 m/s) at a distance of <100 km sufficiently late in the mission to permit reliable corrections for comet-induced non-gravitational forces.

(2) More accurate mass data, possible higher order gravity data, and useful radio sounding will require extended measurements ($\sim$1 month) at short distances ($\sim$10 km or less).

(3) Density determination will require mapping the figure of the entire nucleus. If the spin axis is near the orbital plane, this will require imaging data over a major portion of the mission, including the pre-perihelion phase.

F. RECOMMENDATIONS

The Mass Determination, Radar, and Radio Science Subgroup recommends that the following steps be implemented to ensure that the objectives summarized in Section VIII-B are achieved during the rendezvous phase of a Halley/Tempel 2 mission:

(1) Ensure the development of engineering instrumentation; e.g., a radar altimeter is needed to permit mass and density measurements to about 10 percent or better.

(2) Continue ongoing studies directed toward identifying instrumentation and mission strategy, especially Earth-spacecraft radio tracking which will permit more accurate mass and density measurements, as well as measurement of deviations of the gravitational field of the nucleus from spherical symmetry.

(3) Continue development of the radar sounding instrument as a possible means of studying the internal structure of the nucleus.

(4) Study in more detail the navigation requirements to permit extended periods of operation in the near vicinity (i.e., $<\sim$10 km) of the nucleus, at heliocentric distances sufficiently large to minimize non-gravitational forces on the spacecraft.

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SECTION IX

REPORT OF THE HALLEY PROBE SUBGROUP

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A. INTRODUCTION

Because the main spacecraft must survive the Halley flyby in good condition, it must stay outside the region of dust emitted by Halley. As discussed in more detail in Part One, Section V, the optimum trajectory is a sunward flyby with a closest approach distance of approximately 130,000 km. From this distance:

(1) The proposed imaging system can observe (in conjunction with Earth-based observations) details of the three-dimensional nature of structures in the coma and tail and possibly resolve the nucleus on a scale of 2 km per line pair.

(2) Remote sensing spectrometers can yield some data on the composition and distribution of gases in the coma.

(3) Plasma instruments can detect the largest scale features of the comet/solar wind interaction, such as mass loading of the wind and perhaps the formation of a bow shock.

Of the observations made from the rendezvous spacecraft, only the plasma physics measurements, the possible resolution of the nucleus, and stereoscopic imaging of tail and coma structures would be qualitatively different from observations that can be made from the ground or from Earth orbit. The major discoveries of the remote sensing instruments would come from the considerably greater resolution and sensitivity allowed by a closer view.

B. NEED FOR A PROBE

A very large advance in the scientific return from the Halley flyby can be achieved by sending a short-lived, expendable probe directly into the coma:

(1) Only with a probe is it possible to detect those atmospheric species which do not have convenient spectral lines and thus have to be measured directly. Studies from the main spacecraft are limited because, even though the neutral coma probably extends about 2×10^5 km from the nucleus, only the free-radical end products of the physical and chemical processes in the coma reach such distances, and existing mass spectrometers do not have the sensitivity needed to detect species at such low densities. Only with a probe is it possible to intrude into the collisional zone (radius about 10^3 km) to study *in situ* the nature and effects of chemical reactions which destroy the parent molecules.

(2) Only with a probe is it possible to get unambiguous information about the composition and flux of the dust particles emitted by Halley.

(3) Only with a probe is it possible to study the main features of the comet/solar wind interaction. The regions of ionization of coma gases and their subsequent acceleration into the tail, the postulated tangential discontinuity which separates cometary streamlines from solar wind streamlines, and the postulated inner shock are almost certainly too close to the nucleus to be observed by the main spacecraft.

(4) Without a very long focal length camera on the main spacecraft, a probe makes it possible to image the nucleus at sufficiently high resolution to determine the general physical state of the nucleus. Such information would be valuable for understanding the supply of material to the coma as well as providing a solid basis for a direct comparison of the structure of the nucleus of two very different comets.

The Subgroup concludes that a coma probe is necessary to obtain the types of data needed to perform a comparative study of the two comets, Halley and Tempel 2. Furthermore, the combination of probe and main spacecraft data is much more valuable than data from a single spacecraft only. Plasma measurements on the main spacecraft can provide the baseline or source parameters for the study of the comet-solar wind interaction. In addition, the imaging and remote sensing instruments on the main spacecraft can be extremely helpful in the interpretation of probe data by revealing the large-scale structures and inhomogeneities through which the probe passes.

C. SCIENTIFIC OBJECTIVES

The scientific objectives of the probe are therefore the same as the objectives of the mission as a whole. The probe payload should be selected to address the following aspects of cometary phenomena:

(1) Composition and flux of dust.

(2) Composition and flux of parent molecules.

(3) Physics and chemistry of the coma.

(4) Physical or plasma mechanisms involved in the solar wind interaction.

(5) Appearance of the nucleus.

D. INSTRUMENTS

A representative payload might consist of the instruments listed in Table 2-10. Preliminary studies of probe capabilities indicate it is probably possible to accommodate an instrument mass, power, and bit rate of approximately the amounts shown. The payload in Table 2-10 is similar to, but differs from, the model payload presently under study for the European Space Agency [ESA Report SCI/SPL(79)2, Paris, March 1979]. The Subgroup has included one more instrument, the plasma wave analyzer, and allotted slightly less mass to some of the other instruments.

Two different types of instruments are included for the study of dust. The first type determines the composition of individual dust grains by analyzing the mass distribution of ions created by the high-velocity (57-km/s) impact of grains with a target surface. The second type, the "dust counter", uses the large surface area (≥ 1 m^2) of the planned dust shield on the leading edge of the probe spacecraft as a sensor for dust impacts. It would record the rate of impacts as a function of energy or momentum (depending on the type of sensor used), but would give no information on composition.

The neutral mass spectrometer is discussed in more detail in the Report of the Mass Spectrometry Subgroup (Section III).

Table 2-10 includes both an ion mass spectrometer and a proton analyzer for two reasons:

(1) Because of the high flyby speed and the probable inhomogeneity of the coma, the ion properties may change appreciably during the time required for the ion mass spectrometer to obtain good three-dimensional velocity and mass distributions; thus, a separate, faster normalizing measurement may be required.

(2) The nominal direction of incidence of the cometary and solar wind plasmas are approximately 120 deg apart.

Table 2-10. Representative Prove Payload

Instrument	Mass, kg	Power, W	Maximum Data Rate, kb/s
Dust analyzer	8	10	3
Dust counter	1	1-1/2	0.1
Neutral mass spectrometer	7	8	2
Ion mass spectrometer	7-1/2	5	1.6
Electron and proton analyzer	5	5	1
Magnetometer	3-1/2	3-1/2	1
Plasma wave analyzer	3	3	1
Camera	5	7	2.5
Total for eight instruments	40	43	12.2

The electron analyzer should be able to measure electron temperatures as low as 10^3 K as well as electron energies as high as several keV. A complete plasma package of ion, electron, magnetic field, and plasma wave instruments is recommended to yield an unambiguous interpretation of the data. The availability and technological readiness of the recommended fields and particles instruments are discussed in the Report of the Plasma Physics Subgroup (Section II).

The camera on the probe must be extremely simple to fit within the mass, power, and data rate constraints of the Halley probe. The Subgroup believes that with a simple line-scan camera, it would be possible to increase the 2-km/line-pair resolution of the nucleus by the imaging system on the rendezvous spacecraft to 100 to 500 m/line pair for a 1500-km miss distance. Besides this single high-resolution picture, a probe camera would yield precise information on the actual trajectory of the probe relative to the nucleus. This measurement is important for the interpretation of data from all other experiments on the probe.

E. MISSION STRATEGY

There are many reasons why it is desirable to aim the probe to pass as close to the nucleus as possible:

(1) To obtain the highest quality data from the neutral mass spectrometer.

(2) To increase the chance of observing parent molecules.

(3) To detect purely cometary ion distributions uncontaminated by solar wind.

(4) To obtain a picture with as high spatial resolution as possible.

For the nominal mission plan, in which the probe is released about 15 days before closest approach to Halley and the main spacecraft is then deflected to pass 130,000 km sunward, the targeting uncertainty (1σ) is approximately 750 km. Most experiments would benefit appreciably from a smaller miss distance.

Coping with the dust hazard is of overwhelming importance to the probe's success. There must be shielding to give adequate protection to the spacecraft and experiments as close to the nucleus as possible. Although every effort, both theoretical and experimental, to understand the dust environment is strongly encouraged, there will remain a large uncertainty in the overall dust production rate and its potential for damage.

The desire to get close to the nucleus combined with the uncertainty of the dust hazard means that the probability that the probe may not survive until closest approach may be fairly large. The Subgroup feels that the potential gain in scientific data is worth the risk.

The telemetry rate should be as high as possible for the 75 min when the probe is closer to the nucleus than the closest approach distance of the main spacecraft, or 130,000 km. As indicated earlier, a practical maximum bit rate is probably on the order of 10^4 b/s. However, it would be extremely valuable to operate some of the experiments (dust analyzer and plasma instruments) as continuously as possible from the time of release from the main spacecraft because:

(1) When the probe is close to the main spacecraft, their instruments can be cross-calibrated through simultaneous measurements.

(2) At greater separations, two-point measurements will allow the determination of gradients of properties such as the mass loading of the solar wind.

Thus, we note that even a low bit rate (tens of bits/second) or intermittent sampling could provide very useful information throughout the approach interval.

Finally, the power should be rationed to allow operation out to 130,000 km after closest approach in case the probe survives its passage through the inner coma.